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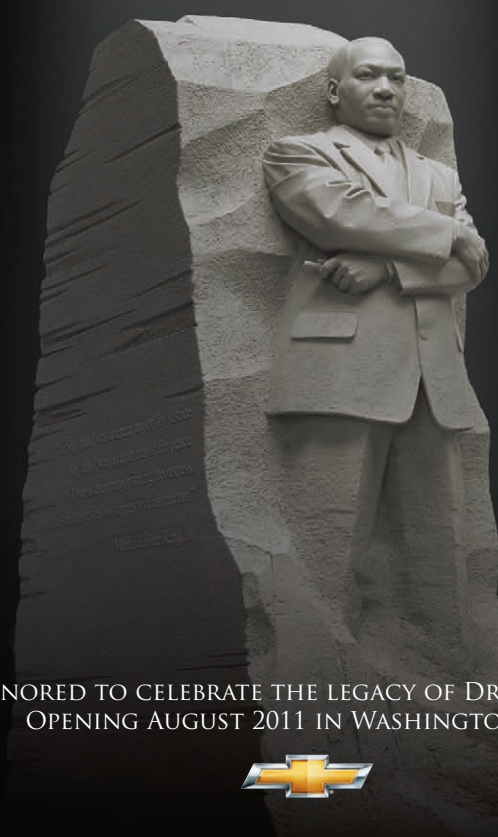

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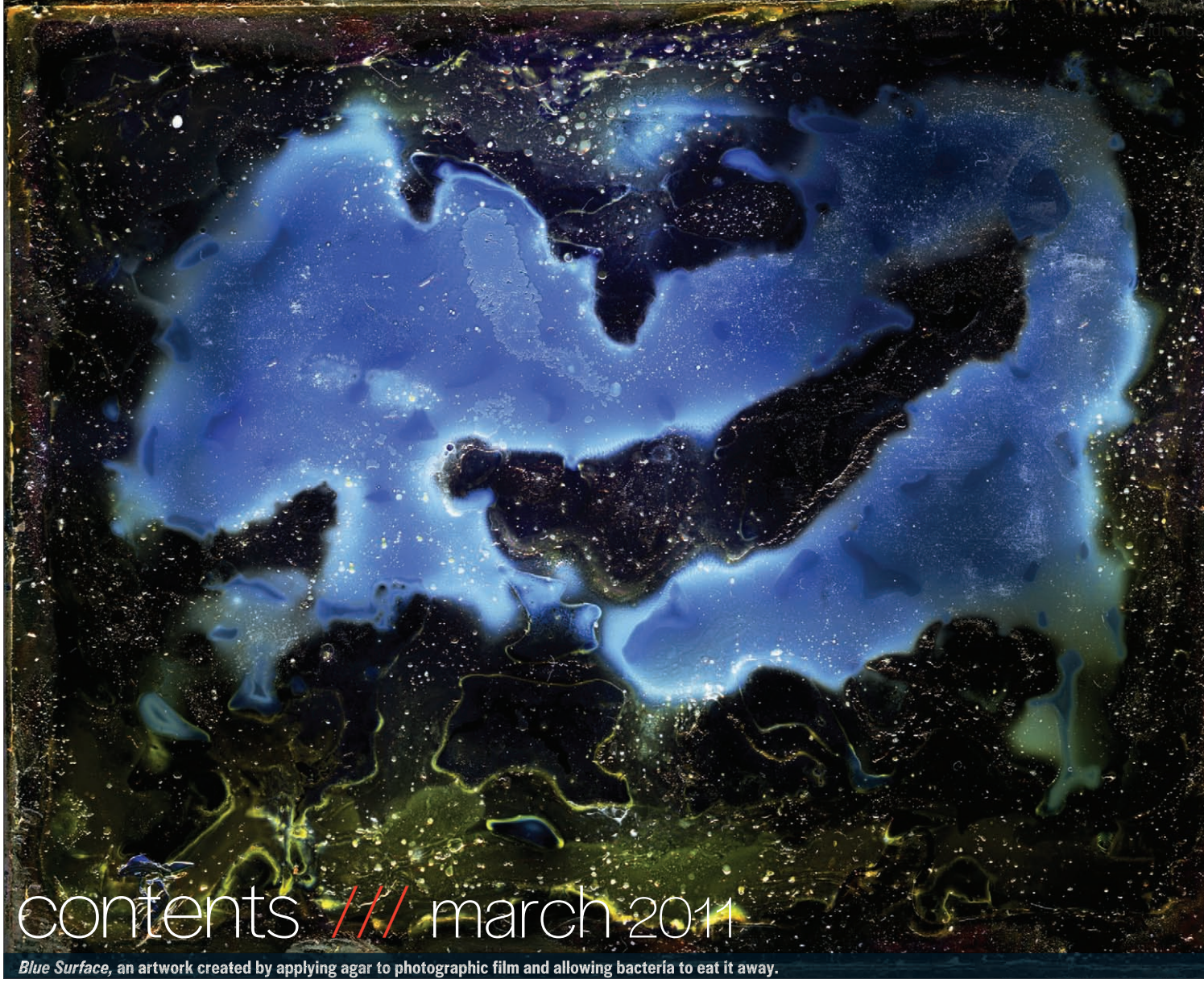

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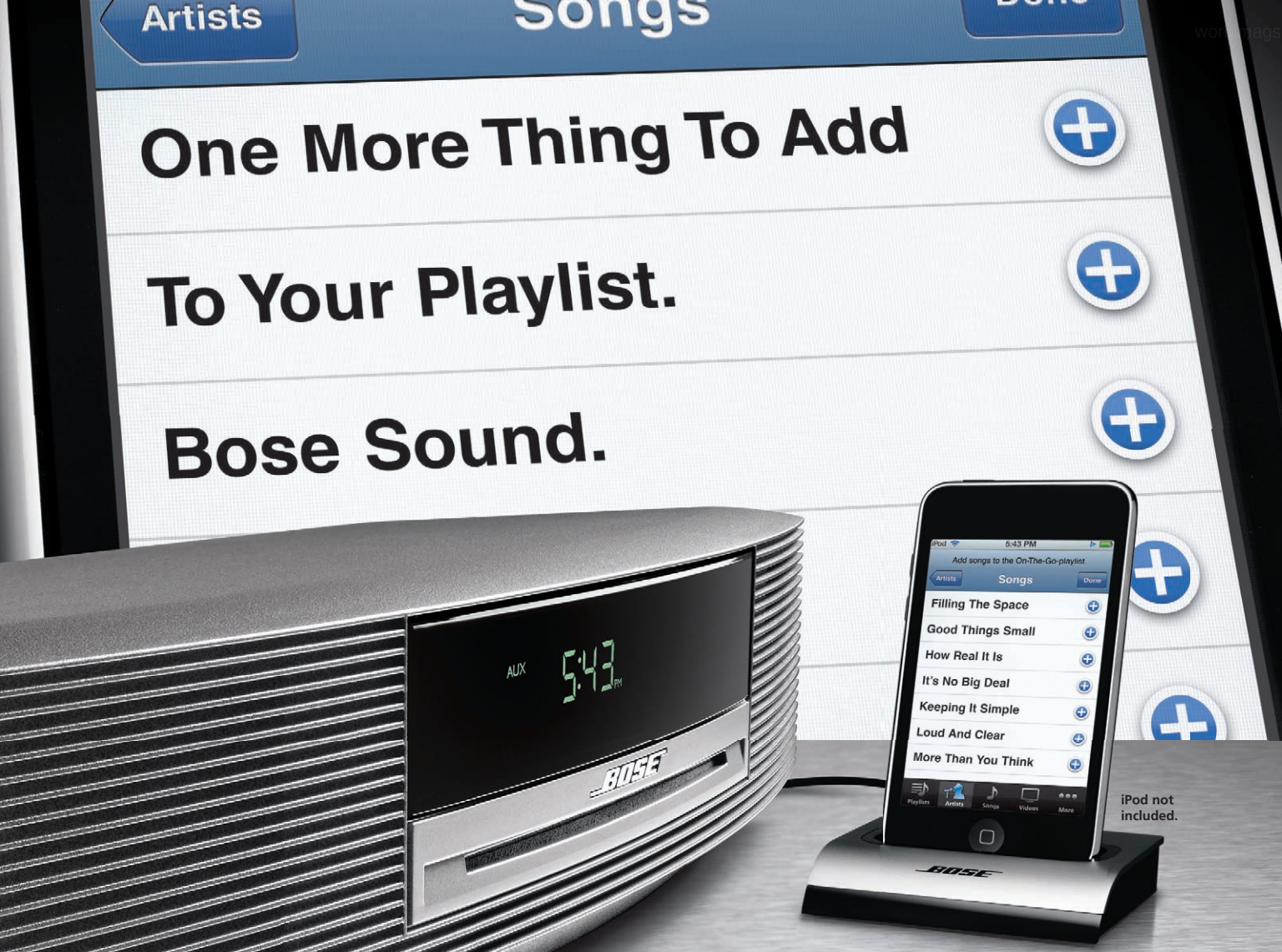
Blue Surface, an artwork created by applying agar to photographic film and allowing bacteria to eat it away.



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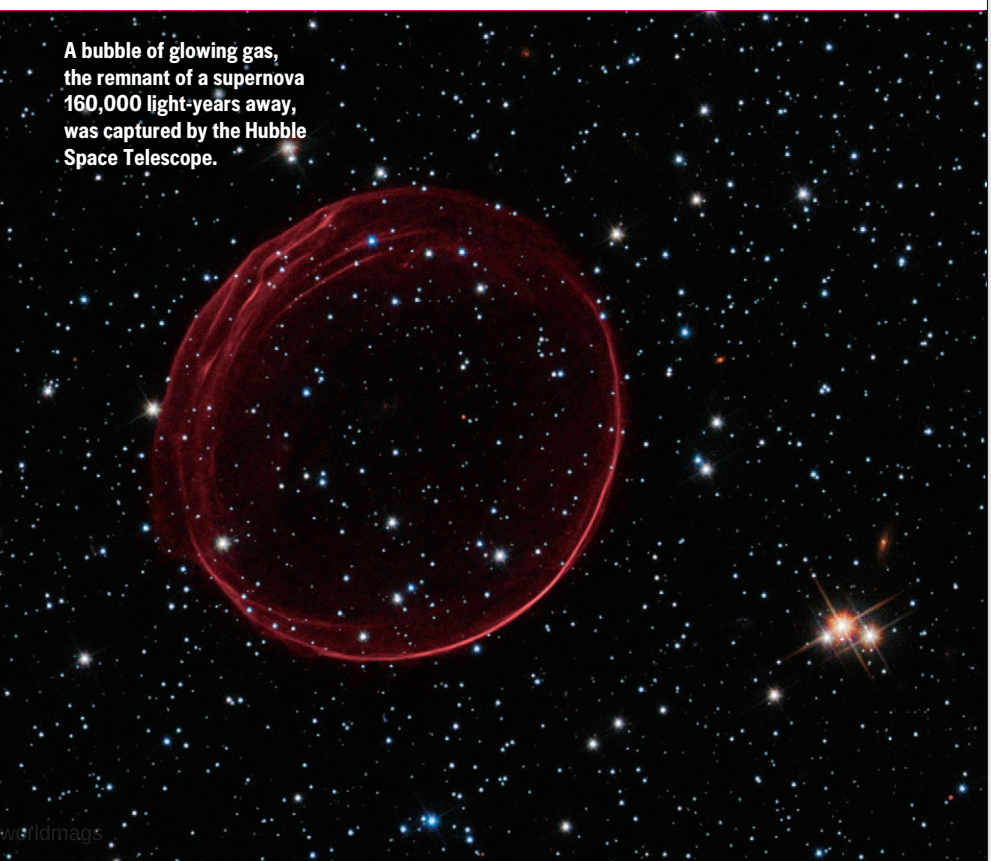

A bubble of glowing gas, the remnant of a supernova 160,000 light-years away, was captured by the Hubble Space Telescope.

NASA, ESA, AND THE HUBBLE HERITAGE TEAM (STSCI/AURA). ACKNOWLEDGMENT: J. HUGHES (RUTGERS UNIV.). PAGE 2: CALEB CHARLAND

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Beats in the Brain **In his column The Brain (page 28), Carl Zimmer explored the latest scientific thinking on the origin of music in the brain and its role in human evolution.** Neuroscientist Aniruddh Patel asserts that music is a cultural invention derived from brain functions. I would argue that music supplied the foundation for brain development, not the other way around. In other words, music came first and other kinds of thinking grew from it. Rhythm is the core of music, and humans understood rhythm (through the beating heart and breathing) even before they had language or mathematics.

Dorothea Steinke
LAFAYETTE, CO

Your article on the evolution of music missed the boat. Speech is music! We all use unique speech melodies and rhythms, which complement facial expressions and gestures for communication. Speech music is a good indicator of ethnicity, which causes unfortunate prejudice today, but thousands of years ago it probably helped early humans determine who was friend and who was foe.

Timothy Miller
STOCKTON, CA

Turbine Turbulence **In "Inherit the Wind" (page 52), Erik Vance profiled JoeBen Bevirt, an entrepreneur whose firm, Joby Energy, is developing flying turbines to harvest energy from winds.** The description of the Joby Energy airborne wind turbine makes no mention of a tether, despite the fact that every other company is developing tethered devices. How else to get the electricity to the ground? And how efficient are the turbines if they require so much energy just to stay aloft?

Sent Visser
GEORGETOWN, TX

Joby Energy's flying turbines sounded like a good idea until I realized that each one would require a huge chunk of airspace to keep from becoming entangled with another. The list of potential problems also includes tornadoes, hurricanes, errant airplanes, and as Ben Franklin discovered, lightning.

William Moreno
CALABASAS, CA

The editors reply:
Joby Energy's prototype wind turbine uses a composite tether to both moor the device and transmit energy to a station on the ground. Once installed, the turbines would be identified on flight charts to prevent aviation mishaps and would be grounded in anticipation of extreme weather, according to Bevirt. For a detailed look at the Joby technology, check out www.jobyenergy.com/tech.

Interestingly, it is possible to wirelessly beam energy over long distances. Japan and California, for instance, have announced plans to install solar panels in space that collect energy and beam it to Earth as radio waves or microwaves, which stations on the ground can convert into electricity.

Is Free Will a Myth? **Neuroscientist Antonio Damasio and novelist Siri Hustvedt discussed the deep mysteries of consciousness and free will in "Of Two Minds" (page 64).** Damasio and Hustvedt explain that when making a decision to move a finger, a person does not become conscious of the action until after the brain has issued the command to move. Damasio contrasts that with more important decisions (like choosing whom to marry), arguing that we still have free will for these decisions because we have time to deliberate and reflect. But no matter how long such deliberations may take, each of the thoughts involved emerges "in the moment" from the interactions of millions of neurons—interactions just as unavailable to consciousness as those leading to the motion of a finger. It is interesting that Damasio accepts the absence of free will in the finger example but not in choosing a partner.

Norm Bearrentine
OAKLAND, CA

Send email to editorial@discovermagazine.com. Address letters to DISCOVER, 90 Fifth Avenue, New York, NY 10011. Include your full name, address, and daytime phone number.

Rebecca Coffey found herself turning into an arachnophile while reporting "20 Things You Didn't Know About Spiders" (page 80). During her research, she spoke with spider wrangler Steven Kutcher, who trained an aggressive spider to land on the actor Tobey Maguire on the set of the movie *Spider-Man*. "Steve somehow convinced this spider to spin down, but he couldn't guarantee that it wouldn't bite," she says. Coffey is currently at work on *Nietzsche's Angel Food Cake (and Other Recipes for the Intellectually Famished)*, a book of faux recipes supposedly written by legendary philosophers, scientists, and authors. She also writes for *Scientific American,* contributes to Vermont Public Radio, and recently completed a fictional autobiography of Anna Freud.

Kat McGowan delves into human consciousness for her feature "Back From the Brink" (page 62), which explores the awareness of brain-damaged patients who are stuck in a semiconscious state. "It's haunting to learn about the limbo these patients are in," McGowan says. "There's no easy mental category to put them in." McGowan is a contributing editor at DISCOVER and edits the magazine's newsstand-only special issues, including "Genius: Great Minds of Science," which is on sale now. She also writes for *Self* and *Psychology Today.* Her DISCOVER feature "Out of the Past" was chosen for *The Best American Science and Nature Writing of 2010.*

Carl Zimmer investigates the teenage mind in the latest installment of his monthly column, The Brain (page 28). "Adolescence is often considered this weird period when teenagers make stupid decisions, but psychologists are starting to look at it differently. Rats and monkeys have adolescent phases too, so we can't just blame the problems on our civilization," says Zimmer, who found that the real culprit may be the uneven way that the brain matures. Zimmer is a contributing editor at DISCOVER. His new e-book, *Brain Cuttings*—a collection of essays exploring the frontiers of neuroscience—is available for download at Amazon, Barnes & Noble, and Mobipocket. He also writes The Loom, an award-winning blog about life past and future; go to blogs.discovermagazine.com/loom.

Andrew Kornylak began his career on steep ledges, photographing rock climbers as he clambered up mountains beside them. In 2006 he ventured into a dark forest in Conyers, Georgia, to shoot a nighttime bike race. Unbeknownst to one passing biker, Kornylak shot a 30-second flash-free exposure, capturing the light from the rider's headlamp; the resulting photograph showed a bright streak of light weaving along a narrow path through the trees. This image inspired Kornylak's photo shoot for "Weaving a New Web" (page 54), based on a roundtable discussion about the future of the Internet. "We wanted to see the panelists' faces, but we also wanted something abstract and cool looking to illustrate the theme," says Kornylak, who, as a former software developer, was fascinated by the topic. Kornylak's images have appeared in *National Geographic Adventure* and *Outside*. You can also view his work on his blog (theblindmonkey.com) and Web site (akornphoto.com). AMY BARTH

science and spirit

MIXING SCIENCE AND RELIGION IS A GOOD recipe for sounding foolish. Albert Einstein, who often invoked God in his criticisms of quantum physics, was rebuked by his colleagues. "Stop telling God what to do," Niels Bohr once retorted. On the other side, Pope Pius XII enthusiastically promoted the Big Bang as supporting the book of Genesis, only to receive distressed messages from members of the Vatican unnerved by the idea of tying the Church to a scientific theory that could be disproved.

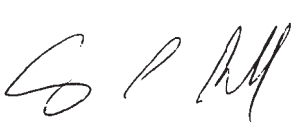
All the same, people keep trying to bring the two together. The impulse is easy to understand. Both science and religion seek an underlying order to the world, and both seek the prior cause that brought the world to the state it is in today. The problem is that their means are very different. Science demands observation and requires that its ideas be falsifiable. Religion ultimately rests on untestable faith.

While I'm casting stones, I should confess my sin: I made my own attempt to explore the common ground between science and religion in my book, *God in the Equation.* (In retrospect, parts of my conclusion plunge right into foolish territory, as some Amazon reviewers not so shyly informed me.) So I am particularly intrigued by the ongoing research of John Polkinghorne, the physicist-priest whose efforts to uncover scientific phenomena that could validate the existence of God are described on page 48 of this issue.

Polkinghorne zeros in on the baffling behavior of the quantum world—on the same sorts of experiments that so confounded Einstein. I say "baffling" because quantum events appear to unfold in a statistical, sometimes random way. That unpredictability might mask some deeper, hidden mechanism, and in Polkinghorne's view, that mechanism could actually be a divine intelligence. It's a clever argument and yet, to me, an oddly narrow one. It treats God as a particle physicist, monkeying with reality one electron at a time. It ignores the far grander marvel of the universe as a whole.

Here I find Einstein's brand of scientific spirituality much more satisfying. Following the ideas of rationalist philosopher Baruch Spinoza, Einstein conceived of God as defined by the laws of physics, and vice versa. In this view, scientific inquiry is a spiritual undertaking no matter what perspective you start from. To those with traditional religious faith (if I may use such a broad brush), studying the cosmos is communing with the work of the Creator. To those who start from a materialistic spot, science is a way to understand laws that connect us to everything else out there, across space and time. Either way, the vastness beyond ourselves is humbling, our ability to comprehend so much of it exhilarating.

Einstein's views are worth repeating at greater length, not only as a summary of Spinozan philosophy but also as a different kind of bridge between the two sides—a demonstration that science can have its own brand of morality. "Spinoza was the first to apply with strict consistency the idea of an all-pervasive determinism to human thought, feeling, and action," Einstein wrote in 1932. "In my opinion, his point of view has not gained general acceptance by all those striving for clarity and logical rigor only because it requires not only consistency of thought, but also unusual integrity, magnanimity, and—modesty."



Corey S. Powell, EDITOR IN CHIEF

What Was It Like to Live during the Middle Ages?

Far from being a time of darkness, the Middle Ages was an essential period in the grand narrative of Western history—one whose developments are an invaluable part of our own modern era. But what was it like to actually *live* in those extraordinary times?

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Coal Gets a Makeover

THE MOMENT A conveyor system unloads coal at the 1,980-megawatt Torrevaldaliga Nord power plant in the Italian port town of Civitavecchia, northwest of Rome. Energy provider Enel completed the plant's conversion from oil-burning boilers to coal-fired ones in 2009. An enclosed belt carries coal from ships into this sealed dome built to contain dust. After combustion, a similar covered system removes ash for use in cement and concrete. Enel says the power station's 45 percent efficiency (a 10 percent gain over the old oil facility), 88 percent reductions in sulfur dioxide and particulate emissions, and 18 percent cut in carbon dioxide make it one of the cleanest coal plants in the world.

THE SHOT Photograph by Alfredo D'Amato using a Canon EOS 5D with EF 17-40mm f/4L USM lens, f/4.0, 1/13 second.

Grabbing Dinner

THE MOMENT A veiled chameleon nabs a cricket. This chameleon can extend its tongue up to twice its body length in just 0.07 second, reaching an acceleration of 41 g's. Expansion and contraction of pigmented cells called chromatophores allow the chameleon to change color, a behavior that seems to serve primarily as a form of communication rather than camouflage. In 2004 biologists reported that this native of Saudi Arabia and Yemen had established a wild breeding population in Florida that probably got its start after thieves broke into an exotic pet dealer's outdoor cages.

THE SHOT Photograph by Scott Linstead with a Nikon D3 and Nikkor 60mm macro lens, f/16, ISO 800. A Phototrap infrared trip wire triggered the camera when the tongue lashed out.

What's the fastest way to learn a language?

ACT LIKE A BABY.

It's not the advice you'd expect. Learning a new language seems formidable, as we recall from years of combat with grammar and translations in school. Yet infants begin at birth. They communicate at eighteen months and speak the language fluently before they go to school. And they never battle translations or grammar explanations along the way. Born into a veritable language jamboree, children figure out language purely from the sounds, objects and interactions around them. Their senses fire up neural circuits that send the stimuli to different language areas in the brain. Meanings fuse to words. Words string into structures. And language erupts.

Three characteristics of the child's language-learning process are crucial for success:

First, and most importantly, a child's natural language-learning ability emerges only in a speech-soaked, immersion environment free of translations and explanations of grammar. Second, a child's language learning is dramatically accelerated by constant feedback from family and friends. Positive correction and persistent reinforcement nurture the child's language and language skills into full communicative expression. Third, children learn through play, whether it's the arm-waving balancing act that announces their first step or the spluttering preamble to their first words. All the conversational chatter skittering through young children's play with parents and playmates — "…what's this…" "…clap, clap your hands…" "…my ball…"— helps children develop language skills that connect them to the world.

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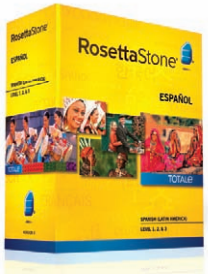

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Should conservationists allow some species to die out?

IN 1987 WILDLIFE SCIENTISTS trapped the last of the 22 living California condors, bred them in captivity, and after five years began releasing the birds. A quarter century later, the condor population stands at 381, with 192 living in the wild. An ongoing monitoring and maintenance program that costs more than $4 million a year helps keep them going.

The divisive question facing conservationists is whether the condor's rescue represents an inspiring success or a waste of limited resources. In October the International Union for Conservation of Nature reported that one in five vertebrates worldwide is threatened, and more join their ranks every year. But funding for conservation is finite, and one outspoken camp of researchers, led by ecologist and mathematician Hugh Possingham of the University of Queensland in Australia, says it is time for the global rescue operation to adopt the mind-set of a battlefield medic: Some endangered species are far more likely to recover than others, so we should identify those and save as many as we can. As for the rest, University of Adelaide ecologist Corey Bradshaw

Wildlife biologists spend $4 million per year to keep the California condor from extinction.

NUMBERS

The Nervous System

BY VALERIE ROSS

268

Speed (in miles per hour) at which signals travel along an alpha motor neuron in the spinal cord, the fastest such transmission in the human body. Sensory receptors in the skin, which lack the speed-boosting insulating layer called a myelin sheath, are among the slowest, at 1 mph.

100,000

Miles of myelin-covered nerve fibers in the brain of an average 20-year-old. Neuroscientists at UCLA, who have studied myelination in the brains of adults ages 23 to 80, reported in September that the coating peaks around age 39–the same age at which participants hit top speeds in standard tests of motor abilities.

says, "It makes no sense to waste money on the doomed if there is no reasonable chance of lifting their numbers into the thousands."

With its small population, high costs, and continued dependence on human intervention, the California condor would probably not make Possingham's priority list. "You could save hundreds of butterfly species with the same investment being put into the condor," he says. Possingham recently analyzed endangered animals and plants in New Zealand and found that for the same budget required to save a single bird species there, the North Island brown kiwi, six other threatened species could be protected.

Conservation triage, as Possingham and others call it, has some commonsense appeal and gives decision makers numbers to latch onto in a field where choices can seem arbitrary. But the idea of prioritizing species and abandoning some to extinction rankles many conservationists. Focusing on the cheapest wins "may increase the short-term tally of species, but we would end up saving only the most convenient ones," says wildlife biologist David Jachowski of the University of Missouri. "Rare or declining species are typically poorly studied, so the easiest to conserve might not be the most ecologically important." Other triage opponents say numbers can be misleading: In the late 19th century, Africa's southern white rhino population appeared headed for extinction, with just 20 or so remaining, but conservation efforts have brought the species to more than 17,000 today. "Predicting survival is far less certain for a threatened species than for a human patient," wrote leaders from 10 conservation organizations in a 2009 critique. Stuart Pimm, a conservation ecologist at Duke University, points out that recovery programs for critically endangered species such as the condor and whooping crane are valuable testing grounds. "These projects teach conservation scientists what works. Pushing the frontier is not cheap," Pimm says.

Possingham knows that many who work in the field are squeamish about his approach but argues that funding realities make triage unavoidable. "People have to accept that we don't have enough money to save everything," he says, and explicitly acknowledging that fact gives conservationists a stronger case for securing more financial support.

Conservationists from both camps have found some common ground. Virtually everyone agrees that successful recovery programs must be grounded in an understanding of why a species is in trouble in the first place. "One of the big lessons of the past is that before you reintroduce a species, you should fix the problem that caused its decline," says Jeff Walters, a biologist at Virginia Tech. For example, following the ban on the pesticide DDT in 1972, bald eagles made a dramatic comeback from just a few hundred nesting pairs in the continental United States in the 1960s to around 10,000 today. Walters cites the Laysan duck as a currently threatened species with a potentially big return on conservation efforts. Nonnative animals such as cats and rats had driven this Hawaiian bird to extinction on all but one island. A second population recently established in the predator-free Midway Atoll National Wildlife Refuge is growing rapidly. "We can make a big impact investing in this species," Walters says.

As for the California condors, they probably remain a long way from thriving on their own. Bradshaw and his colleagues recently surveyed studies of 212 vertebrates and found that the typical minimum viable population size required for a species to survive long-term is about 5,000 individuals. But even in the face of long odds, many laboring to save the most endangered animals remain determined not to let go. "We've worked with these birds for decades with everybody telling us that it was not going to work," says wildlife biologist Mike Wallace of the San Diego Zoo Institute for Conservation Research, who runs the condor program. Given enough time—and money—Wallace hopes he can prove the doubters wrong.

ISABELLE GROC

JOEL SARTORE/NATIONAL GEOGRAPHIC STOCK

Buzz Words

CALIFORNIA CONDOR
This critically endangered species that historically lived along the entire American west coast is being reintroduced into the wild after its population crashed to 22 in the 1980s.

CONSERVATION TRIAGE
The controversial idea that conservation resources should be allocated to species with the best prospects for long-term survival.

LAYSAN DUCK
This Hawaiian-islands native was nearly driven to extinction by introduced predators but is now staging a comeback on an island where the invaders have been banished.

MINIMUM VIABLE POPULATION SIZE
The smallest number of individuals that will give a species a good chance (some biologists use 95 percent) of persisting over a long timeframe (for example, 100 years). One recent analysis suggests that vertebrates need a population of around 5,000.

100 Trillion

Minimum number of neural connections, or synapses, in the human brain. That is at least 1,000 times the number of stars in our galaxy. British researchers reported in December that genes involved in the workings of synapses account for about 7 percent of our genome.

50

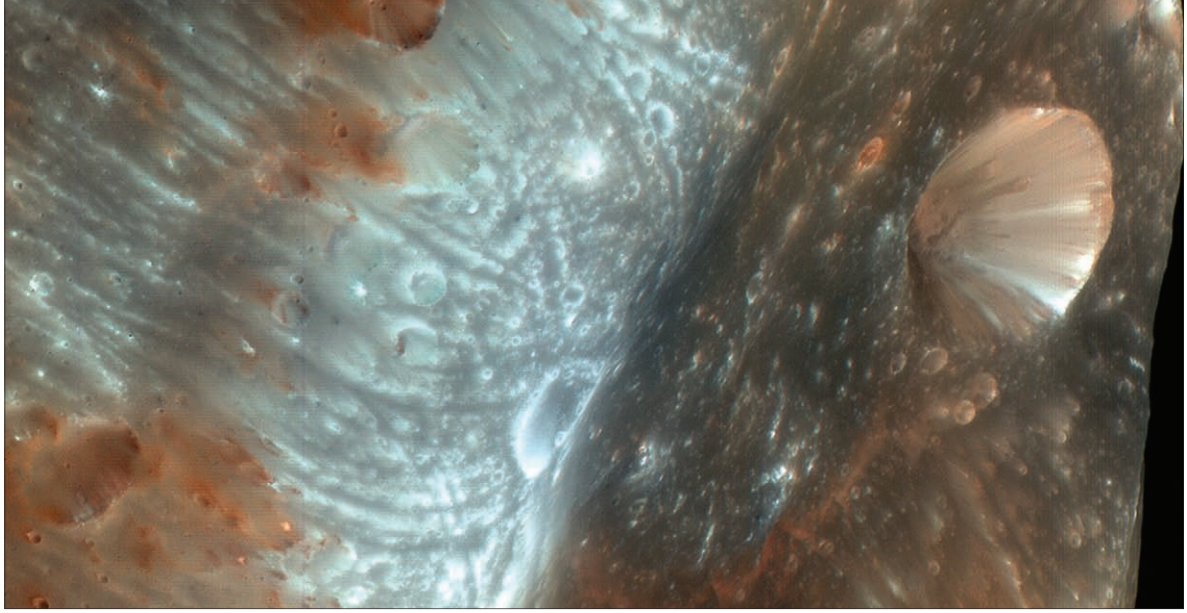
Depth, in nanometers, of the smallest grooves detectable by a human fingertip (that is about 2 millionths of an inch). Most of the 2 billion or so nerve endings in the outermost layer of our skin sense pain; those dedicated to temperature allow us to detect differences as small as 0.01 degree Fahrenheit.

2,000

Number of slices created from the cerebral cortex of a mouse by Harvard University scientists. The researchers will image each slice under an electron microscope and then build a 3-D picture of all of the brain's connections. Someday, similar maps of human brains may yield clues to mental illness, memory, and personality traits.

1 BILLION

Number of neurons, linked by 10 trillion synapses, in a brain simulation developed by IBM and Lawrence Berkeley National Lab, running on the Dawn supercomputer. Researchers are testing hypotheses about how the brain works. The real human brain contains about 100 billion neurons, so scientists are getting close–in raw numbers, at least.



The Martian moon Phobos may be an asteroid captured by Mars's gravity.

SPACE BEAT

NASA Ponders an Asteroid Shot

WITH NASA'S PLANS FOR A NEW round of manned moon landings in 2020 scuttled last year, the agency and its industry partners are considering a more ambitious plan: sending humans to an asteroid.

Such a mission could stretch to tens of millions of miles. The moon, by comparison, is less than a quarter of a million miles from Earth. By boosting our understanding of long-distance human spaceflight, an asteroid trip would provide a valuable warm-up for a crewed visit to the Red Planet. "One of the greatest reasons to go to an asteroid is to test the systems that could take people to Mars," says John Baker, systems engineer with NASA's Jet Propulsion Laboratory. Either standard rocket fuel or efficient solar-electric propulsion could power the craft to a space rock and back, Baker says. Engineer Josh Hopkins of Lockheed Martin, who recently participated in a Washington, D.C., conference devoted to asteroid exploration, agrees that the project would provide "good practice and a learning experience for Mars."

Hopkins is a lead researcher with the *Orion* crew capsule, a potential craft for the asteroid mission. He says that hardware improvements since the Apollo era, such as beefed-up radiation protection and solar arrays for renewable power, are well suited to the longer-duration journey required to reach an asteroid.

The expedition would also provide an opportunity to collect samples from the rock's core for analysis. Understanding asteroid composition could eventually help in devising a way to deflect one on a potential collision course with Earth, Hopkins says. Core samples could also provide insight into the solar system's birth, since many asteroids were formed during our star's infancy some 4.55 billion years ago.

No target asteroid has been selected yet, but researchers are investigating a handful of potential destinations that will come within reach over the next 10 to 20 years.

VICTORIA TANG

ENERGY BEAT

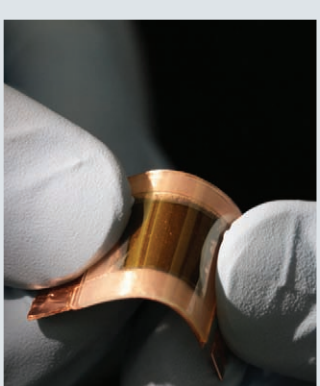
Plant Power

IN A QUEST TO BUILD A BETTER SOLAR cell, North Carolina State University chemical engineer Orlin Velev is borrowing from nature's experts in collecting the sun's energy: leaves. Starting with the natural pigments that help plants harvest solar rays, Velev and his team have crafted a flexible, nontoxic photovoltaic device that he hopes could eventually generate clean electricity far more cheaply than today's silicon-based solar panels.

Velev's one-square-inch prototypes consist of light-sensitive molecules–including the photosynthesis powerhouse chlorophyll–embedded in a water-based gel sandwiched between copper and plastic electrodes. Unlike traditional solar cells, many of which contain toxic elements such as cadmium, the biologically derived materials in Velev's device can be safely released into the environment after use. The cell's flexibility could make it an ideal choice for covering irregular surfaces; large pieces could even be rolled up or folded for easy transportation.

"This is a totally different way of thinking compared to a semiconductor cell, which is solid and expensive," Velev says. In the next stage of development, he aims to boost the efficiency of the design, which is currently less than one percent of that achieved by top-performing silicon solar cells.

VICTORIA TANG



A new flexible solar cell uses plant-based ingredients to gather energy.

FROM TOP: NASA/JPL/UNIVERSITY OF ARIZONA; COURTESY ORLIN VELEV

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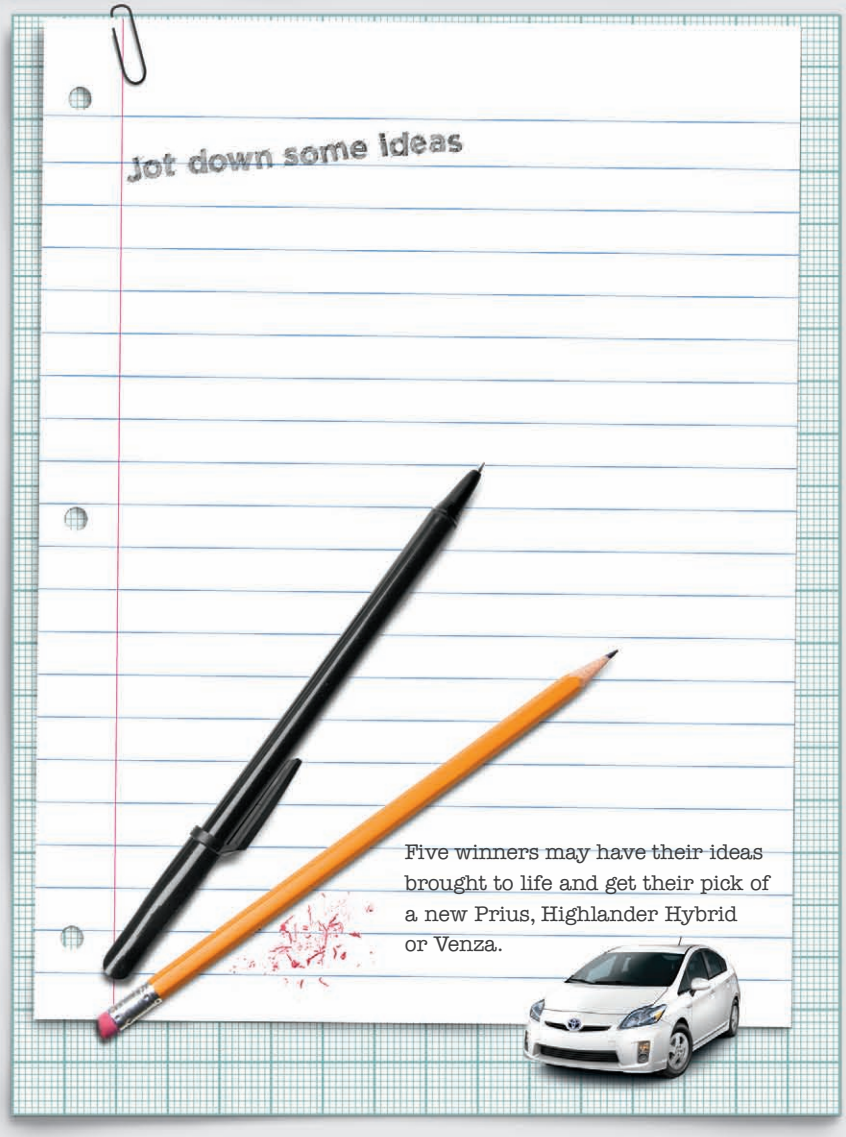


Options shown. **NO PURCHASE NECESSARY TO ENTER OR WIN. PURCHASE WILL NOT INCREASE YOUR CHANCE OF WINNING.** Contest runs 11/8/10 at 12:01 a.m. ET to 2/28/11 at 11:59:59 p.m. ET. Open to legal residents of the 48 contiguous states, 18 years of age and older and not a minor. Void where prohibited. For Official Rules visit www.yourideasforgood.com/rules. Sponsor: Toyota Motor Sales, U.S.A., Inc., 19001 South Western Avenue, Torrance, CA, 90501. [1]The Solar Roof is designed to use a fan to draw outside air into the cabin to lower the cabin temperature to near the outside ambient temperature when reentering the vehicle. It must be turned on prior to leaving the vehicle and cannot perform cooling such as could an air conditioner. [2]The Advanced Parking Guidance System requires driver brake control. Always look around outside the vehicle and use mirrors to confirm clearance. ©2010 Toyota Motor Sales, U.S.A., Inc.

toyota.com

Engineered soybeans resistant to glyphosate account for 93 percent of the soy grown in the United States.

ENVIROMENT BEAT

Rise of the Superweeds

THE AGE-OLD WAR BETWEEN FARMERS and weeds is escalating. Crop-strangling plants are rapidly becoming immune to the most widely used agricultural herbicide, glyphosate, commonly known as Roundup. An estimated 10 million of the 178 million acres of U.S. farmland growing corn, cotton, and soybeans are now infested with weeds that are invulnerable to the chemical. Herbicide resistance could cost nearly $1 billion per year—and may force farmers to reexamine older practices that modern chemicals were supposed to replace.

In the 1990s, when agrotech giant Monsanto introduced genetically modified crops that can withstand glyphosate, many farmers turned to Roundup as their sole herbicide. Initially, that made farming simpler and more efficient. But reliance on a single substance naturally breeds resistance, since the few weeds that survive pass their hardiness to the next generation. "The population quickly shifts from one that is sensitive to the herbicide to one that is largely resistant," says Micheal Owen, a weed scientist at Iowa State University. At least 12 U.S. weed species no longer respond to glyphosate, and since some seeds are windborne, resistance moves easily from one farm to another. Monsanto and other agricultural chemical companies plan to introduce crops that can withstand other herbicides, which could encourage farmers to add more variety to their treatment regimens.

Working with scientists from five other states, Owen is comparing different weed-control practices on about 150 fields throughout the South and Midwest. Preliminary results from the five-year study (funded by Monsanto) suggest that new strategies, such as combining multiple chemicals and applying herbicides both before and after weeds emerge, can improve crop yields compared with the typical glyphosate-heavy approach, while slowing the emergence of resistance. A larger chemical arsenal alone will not solve the problem, but in combination with traditional weed management, such as tilling and crop rotation, it should make it harder for unwanted plants to evolve resistance.

Although many farmers have not yet been affected, Owen stresses the importance of preventive action. "In fields that don't yet have problems, now is the time to make changes," he says. MARA GRUNBAUM

GOOD NEWS

➳ An imaginary binge may prevent a real one. Psychologists at Carnegie Mellon University report that people in a study who imagined eating a lot of food, one bite at a time, later **ate about half as much** of that food as those who did not.

➳ Taiwan's EPA found that training pigs to use a toilet area can **reduce the amount of wastewater** from pig farms by as much as 80 percent.

➳ A trial release of genetically sterilized male mosquitoes successfully **reduced the local population** of the dengue-fever-carrying insects on Grand Cayman island.

BAD NEWS

➳ Jet lag may last a lot longer than you think. UC Berkeley psychologists report that hamsters subjected to a disrupted light cycle for 25 days showed **impaired cognitive performance** four weeks after returning to a normal schedule.

➳ A newfound species of iron-eating bacteria is **consuming the wreck of the *Titanic*.** The ship's remains may disappear completely in just 15 years.

➳ Goodbye, Mr. Chips indeed. According to a study of 1.3 million students in North Carolina, most test-score gains achieved by students of top teachers **fade within a year.**

PAULO WHITAKER/REUTERS

DISCOVER MAGAZINE .COM

Keep your finger on the pulse of science as it happens with 80Beats, the DISCOVER news aggregator at **blogs.discovermagazine.com/80beats.**

Discovered in the Jungle

FOR GENERATIONS, RESEARCHERS DISmissed the Amazon as a cultural desert, a jungle terrain too treacherous to support any civilization more sophisticated than nomadic tribes. But in recent years archaeologists have uncovered evidence of ancient, densely populated settlements throughout the basin, hinting at societies far larger and more advanced than previously thought.

Some of the most eye-opening new research comes from the western Amazon, where archaeologist Denise Schaan of the Federal University of Pará in Brazil has mapped clusters of mysterious land sculptures dug between 700 and 2,000 years ago. The purpose of the 269 circular and rectangular earthworks, scattered over a 15,000-square-mile area, remains unknown, but Schaan suspects they were ceremonial platforms. "These earthworks could only have been built by large, coordinated populations," she says. Exactly how large is difficult to say. Based on analysis of the region's charcoal-enriched sediment—which may have been intentionally or incidentally fertilized by human occupants—University of Wisconsin geographer emeritus Bill Denevan estimates that up to 9 million people may have lived in the 15th-century Amazon.

Brazilian archaeologist Helena Lima of the Federal University of Amazonas believes the newly discovered settlements have a long history. In addition to hundreds of carvings of human faces approximately 3,000 to 7,000 years old, Lima also discovered pottery artifacts suggesting a network of connected villages covering the central Amazon.

Although a jungle may seem an unlikely home for thriving civilizations, one researcher suggests that the ancient landscape could have been strikingly different. Archaeologist Augusto Oyuela-Caycedo of the University of Florida reports that remnants of corn and other crops in northeastern Peru indicate that large swaths of the region were actually gentle grasslands carefully managed by the inhabitants. WILL HUNT

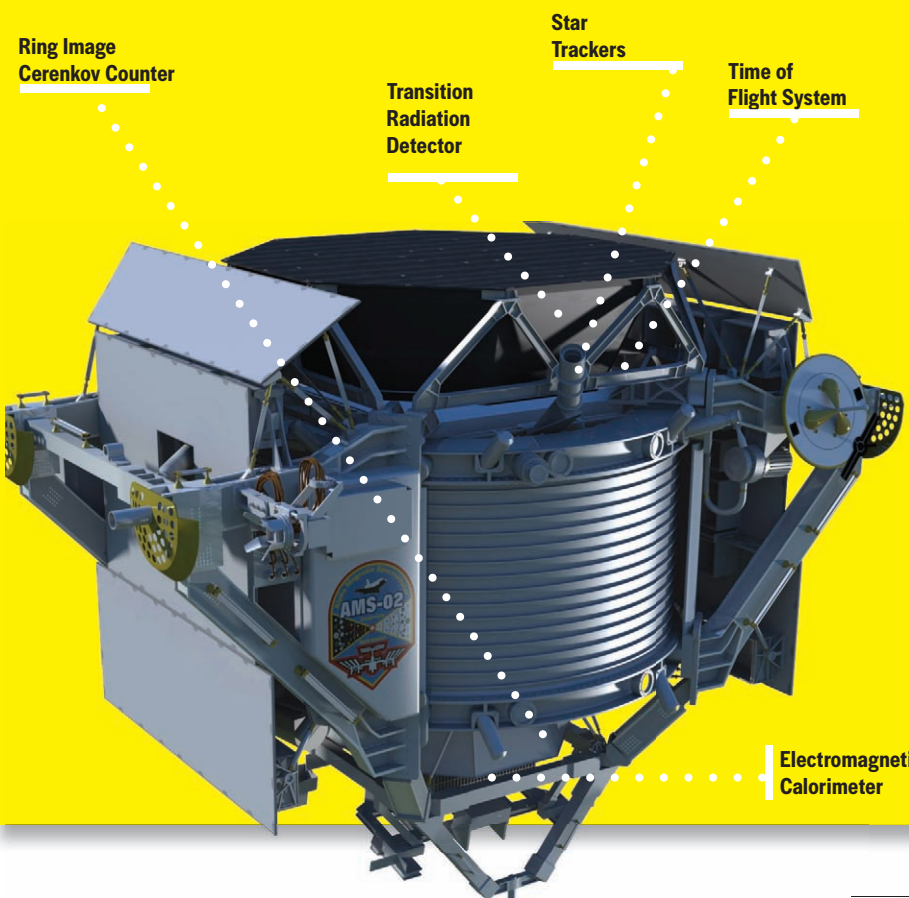
Tools of the Trade | AMS

Alpha Magnetic Spectrometer

When the space shuttle *Endeavour* makes its final visit to the International Space Station this spring, it will leave behind a 7.8-ton parting gift: an automated particle detector called the Alpha Magnetic Spectrometer (AMS), which will attach to the station. Each second, the AMS will encounter 25,000 cosmic rays–high-speed atomic and subatomic particles (some from the sun, some from deep space), the most energetic of which pack hundreds of times as much energy as anything a scientist can whip up in an Earth-based particle accelerator. The 650 computers in the instrument will track the particles' trajectory, speed, and energy, which the device's designers hope will provide insights into mysterious forms of matter, including antimatter, dark matter, and a hypothetical family of particles called strangelets.

When a particle enters the AMS, it passes through a gauntlet of experiments that pry information from the interloper. Each particle entering the **transition radiation detector** releases radiation that hints at its mass. Next, the silicon tracker charts the particle's path based on the electric current it leaves in its wake, while the **time of flight system** measures its velocity. A **ring image Cerenkov counter** analyzes the spray of light given off by particles as they crash through a porous material called an aerogel; that light reveals the particles' speed before their final collision into the energy-measuring **electromagnetic calorimeter**–a lead brick laced with optical fibers. All the while, two GPS-enabled **star trackers** keep the AMS oriented correctly and a thermal system keeps all the equipment within its proper operating temperature range of -40 to 90 degrees Fahrenheit.

More than 500 participants from 16 countries are collaborating on the $2 billion AMS. "It's probing the foundations of the universe," says NASA project manager Trent D. Martin. "We'll collect data for 10 years and then study it for 30 or 40." JOSEPH CALAMIA



COURTESY MIT

Geyser

Geysers gush massive columns of hot water and steam from fissures in the ground, offering a rare look at the earth's inner workings. The best place to see one is Yellowstone National Park, where more than half of the 1,000 or so active geysers in the world (including Castle Geyser, pictured) feed off the heat of an enormous subterranean volcano. The activity begins deep in a geyser's underground plumbing, where high-pressure water boils, sending bubbles up through a narrow column of water within the overlying rock. The bubbles eventually gain enough force to push some water out of the spout, decreasing the pressure on the deeper water and causing it to boil even more furiously. The result is an eruption that can rise hundreds of feet in the air. In recent years, researchers have applied their understanding of geysers to endeavors as diverse as clean energy and planetary science. MARA GRUNBAUM

HOT HOT HEAT ENERGY Water ejected by geysers can be as hot as 400 degrees Fahrenheit. Some engineers are hoping to tap into that buried thermal energy and convert it to electricity. In December, power company Crump Geothermal began drilling wells around a geyser in southern Oregon. Crump believes that the geyser's underground reservoir could support a 30-megawatt plant capable of powering 30,000 homes.

QUAKE MAINTENANCE Geysers tend to die out because mineral buildup clogs their nozzle. The geysers in Yellowstone are so active partly because frequent earthquakes shake loose the debris as quickly as it accumulates. In early 2010, seismologists measured more than 1,700 minor quakes in less than three weeks.

CLOUDY WITH A CHANCE OF ERUPTION Yellowstone's Old Faithful geyser is famous for its near-clocklike regularity, but scientists with the U.S. Geological Survey recently determined that annual precipitation influences the overall frequency of eruptions in Yellowstone: The more it rains and snows nearby, the more often the geysers pop. The geologists think that geysers depend on surface water to seep down and build up pressure in the groundwater supply.

PLUMES IN SPACE NASA scientists at the Jet Propulsion Laboratory in Pasadena have used the mechanics of Old Faithful to try to explain the gigantic plumes of gas and ice crystals, appropriately known as "Cold Faithful," on Saturn's moon Enceladus. Like their terrestrial counterparts, the icy geysers spout gas-charged fluids from an underground chamber. The scientists hope to find out whether that chamber contains liquid water, making it a potential hotbed for life.

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Five Questions for

Jacob Hanna

TWO MONTHS AFTER LEAVING HOME FOR COLlege in Jerusalem, Jacob Hanna was still seeking a place to live; some of his prospective landlords were reluctant to rent to a Palestinian. Undeterred, he found an apartment, earned his degree, and then headed to MIT. There, his research manipulating stem cells earned him job opportunities at NYU and Harvard. Instead, the 31-year-old plans to return to his native Israel to start a lab at the Weizmann Institute of Science.

You made a name for yourself by curing mice of sickle-cell anemia. How did you do that?

We converted mouse skin cells into induced pluripotent stem cells—undifferentiated cells that can be used to generate any tissue in the body. Then we corrected the sickle-cell mutations in those cells and injected them back into the diseased mice. By relying on the mouse's own cells, you don't need donors or immunosuppressants to prevent rejection.

How could this work apply to humans?

Usually human stem cells that we grow in the lab have already begun to differentiate, but last year my team provided the first evidence that we can maintain them in a more naive state.

Stem cell research has attracted a lot of hype. Is it hard doing research under those conditions?

Several times I have tried to continue the work of others, only to find that addiction to media attention had driven some stem cell researchers to make outrageous claims.

What was your education like in Israel?

There is active segregation between Palestinians and Israeli society. If you're a minority and want to get educated and get a job, you have to push for it. The system is not helping you out.

Then why go back to Israel to start your laboratory?

Academia is perhaps the only environment in Israel where people interact without differences, and Weizmann is a great multidisciplinary institute. There is also value added in promoting Palestinian academics. If I could assist with that, it would bring me great satisfaction.

ANDREW GRANT

PHOTOGRAPH BY CHRISTOPHER CHURCHILL. GROOMING BY KACIE CORBELLE/ENNIS

HOT SCIENCE

What to read, view, and visit this month

TV

The Event

ORIGINALLY HYPED AS THE new *Lost,* creator Nick Wauters's NBC drama hit its stride as its own distinct mashup of sci-fi genres—alien invasion, government conspiracy, fugitive on the lam—with plenty of twists to come as the show returns for the second half of its debut season this spring.

Blair Underwood stars as the newly elected president who plans to defy counsel and free a shadowy group of aliens imprisoned for decades by the United States government. Laura Innes portrays Sophia Maguire, leader of the alien detainees, with an enigmatic blend of maternal empathy and steely resolve, while Jason Ritter brings a hangdog intelligence to the role of Sean Walker, an MIT computer geek who inadvertently discovers the clandestine operation while searching for his abducted girlfriend.

Sagging ratings could dash hopes for a second season, but that's not necessarily a bad thing: Pressed for time, *The Event* moves along briskly, with new revelations coming fast and furious. Catch it while you can.

Mondays, 9 p.m. EDT.

COREY S. POWELL

Catch up on *The Event* at NBC.com. New episodes begin February 28.

Books

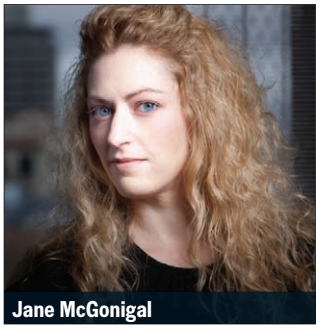
How Games Will Save the World

Reality Is Broken

By Jane McGonigal (PENGUIN)

SINCE THE MULTIPLAYER GAME *World of Warcraft* debuted in 2004, gamers have spent more than 50 billion hours guiding their role-playing avatars through its mythical virtual worlds. That's a combined 6 million years of what game designer Jane McGonigal calls "hard fun"—hard work that's challenging yet satisfying. To McGonigal, the addictive draw of games represents a remarkable opportunity to improve reality, not simply escape from it, because games create a powerful arena for collaboration.

McGonigal points to a recent project in which she helped the World Bank Institute create a free online multiplayer game called *EVOKE* that challenges people around the world to solve major social ills like hunger and poverty. Set in 2020, the game explores a secretive network of superhero problem solvers in Africa and then challenges players to create world-changing ventures of their own within 10 weeks. "There is



Jane McGonigal

FROM LEFT: NBC PHOTO; BART NAGEL

something primal about our desire to play games," McGonigal says. The big challenge for game designers is to figure out smarter ways to tap that desire for the greater good.

Why We Get Fat

By Gary Taubes
(ALFRED A. KNOPF)

TAUBES'S LATEST ADDITION TO THE crowded genre of diet books dismisses as folly the common wisdom of calorie counting. It's not how much we eat, he argues, but *what* we eat that makes us pack on the pounds, The culprits: insulin and hormonal imbalance. Taubes expertly translates the latest scientific thinking on insulin and fat storage but draws conclusions that seem disappointingly familiar: Meat is good, carbs are bad, and exercise just makes you hungrier.

Moonwalking With Einstein

By Joshua Foer
(PENGUIN)

IN RECOUNTING HIS YEAR IN TRAINing for the U. S. Memory Championship, journalist Foer delivers a rich history of memory, beginning with early recorded accounts of "super memory" in ancient Greece. He also shares a few fun mnemonic devices. Need to remember to buy cottage cheese? Build a "memory palace" in which you picture Claudia Schiffer swimming in a vat of the stuff. Technology may be rendering such memory training unnecessary, but Foer sees more than a party trick in his new skills. "It's about nurturing something profoundly and essentially human."

The Ragged Edge of the World

By Eugene Linden
(VIKING)

LINDEN'S GLOBETROTTING TREK explores the steady erosion of wilderness and the impact on indigenous peoples and biodiversity in places like Borneo and New Guinea. A veteran nature writer, Linden is at his best when drawing on a lifetime of adventure stories from remote regions. But his tendency to preach occasionally detracts from his bigger message of conservation.

ELISE MARTON & ANDREW MOSEMAN

Film

Limitless

UNIVERSAL STUDIOS

If anyone needs a wonder drug, it's Eddie Morra. Bradley Cooper's character in this psychological thriller is a bedraggled writer whose career and personal life are languishing until a friend slips him a new psychotropic medication called NZT. On the pills, Eddie's mind kicks into hyperdrive: In a matter of days, he finishes writing a book, learns Italian, and makes a killing on Wall Street. But like any pharmaceutical, NZT has side effects: amnesia, paralysis, homicidal blackouts, and the threat of sudden death. Robert De Niro also stars in this film based on Alan Glynn's 2002 novel *The Dark Fields.* Opens March 18.

MARA GRUNBAUM

Museum

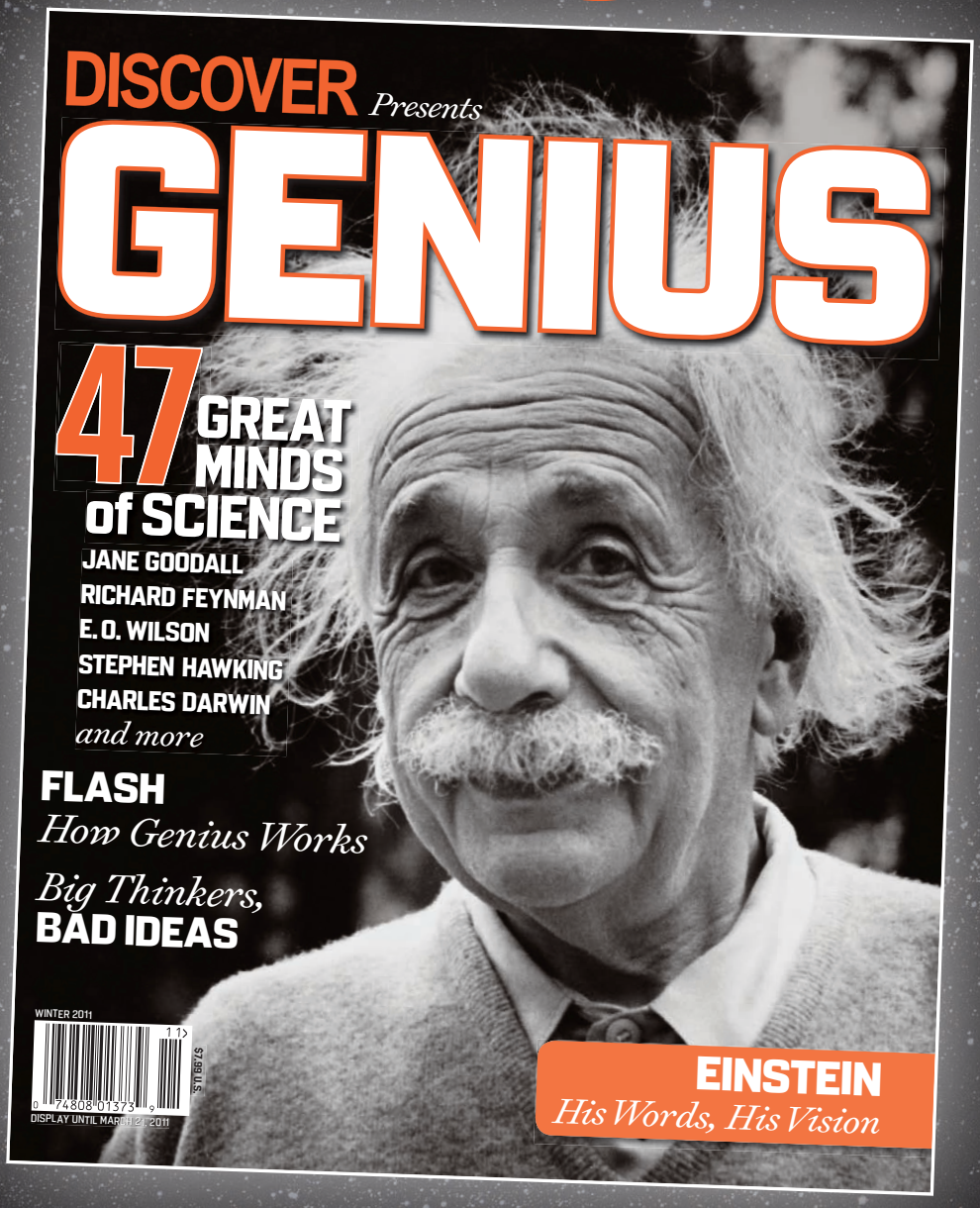
Star Wars: Where Science Meets Imagination

PACIFIC SCIENCE CENTER, SEATTLE

The galaxy far, far away may not be so far away after all. This traveling exhibit, assembled in part by *Star Wars* creator George Lucas's company Lucasfilm and presented by Bose, lets visitors explore the real-life science behind the *Star Wars* universe. Ever want to build your own landspeeder? The Maglev Engineering Design Lab lets you outfit a scaled-down model speeder with a simple magnetic levitation system, and in the process you learn how modern Maglev trains hover above the tracks. The game "Building Communities" asks players to choose technologies to adapt to Luke Skywalker's arid homeworld, such as using moisture collectors to find drinking water. When you're done constructing hovercraft and fending off dehydration, kick back in a replica cockpit of the *Millennium Falcon* for a spectacular view of some of the best images from the Hubble Space Telescope. Opens March 19.

WILL HUNT

What does it take to be a scientific genius?



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VITAL SIGNS

BY H. LEE KAGAN

A faint whiff of bad breath tells a worried wife something is seriously wrong with her husband.

JERRY WAS IN FINE FORM AS HE STOOD AT CENTER STAGE, HIS HAND RESTing on the microphone stand, waiting for the laughter to subside. He had invited me to watch him perform stand-up at this West Los Angeles comedy club, and he didn't disappoint. But his wife, Sandy, wasn't laughing. She leaned across the small cabaret table we were sharing and said, "I need to talk to you about Jerry." They had both been patients of mine for many years. Both were late middle-aged, and neither had ever had a serious medical problem. I looked at her quizzically and she said, "His breath."

I leaned closer and asked, "What about his breath?"

"It's different. Not bad, but it's changed. Something's not right."

"How long?"

"Maybe three months."

I asked if anyone else had mentioned anything, and she shook her head.

"How does he feel?"

"He says he feels fine. But something is wrong. I'm his wife and I can tell. Something has changed."

I looked up at Jerry. He was pulling faces now, mimicking his elderly father as part of his routine. The audience was loving it.

"Have him come see me in the office," I told Sandy.

"HONEST TO GOD, DOC, I'M FINE," Jerry insisted a week later. "If you ask me, I think it's my wife's sniffer that needs a checkup." Jerry did indeed look well, and when I put my face close to his and asked him to exhale through an open mouth, I could detect no unusual or unpleasant odor. Likewise, when I had him breathe out through his nose, nothing struck me as especially noxious.

He told me there had been no recent dental problems, sores in his mouth, or other symptoms. He didn't wear dentures and hadn't begun using any new medications or supplements. The examination of his nose, mouth, tongue, throat, and gums was unremarkable to my internist's eye. I took one more sniff. Nothing. Frankly, I wasn't sure that anything was wrong, but I told him to go see his dentist.

"I was just there three months ago," he protested. "Everything was OK."

I nodded and said, "See him again anyway." Halitosis, defined as a foul or fetid odor carried on the breath, originates in the oral cavity or sinuses 80 to 90 percent of the time. The literature reports that it occurs in about 15 to 30 percent of the population. Since it is often difficult to notice one's own odor, millions of people walk around with bad breath and don't know it.

The malodor of halitosis usually results from the bacterial breakdown of amino acids in food debris, saliva, blood, and postnasal drip in the oral cavity. The residue of everything from caviar to cannoli provides the raw material for the volatile sulfur compounds primarily responsible for the offensive smell. Concentrations of the culpable microbes are particularly heavy in the spaces between the teeth and gums and on the back of the tongue.

The nasal passages and sinuses are the second-most common source of bad breath. Less common causes in the mouth are diseases such as gingivitis. Although an assortment of illnesses—such as advanced kidney disease and liver failure—can cause unpleasant odors on the breath, it is rare for any of them to produce halitosis without any other signs or symptoms.

Two weeks later I got a call from Sandy. "So, what did the dentist find in your husband's mouth?" I asked.

"Nothing," she told me. "The dentist didn't even think his breath was bad. He just told him to floss regularly and gave him a toothbrush. But I know something's wrong. Can't you just give him some antibiotics?" She was obviously frustrated.

I told her I didn't think that was a good idea. Although interdental and gingival sources of malodor may be transiently improved with antibiotics that suppress bacterial counts, in Jerry's case I didn't know what, if anything, I would be treating. "Let me see him in the office again," I suggested.

The following afternoon both Jerry and Sandy sat in my exam room. When I asked him how he was feeling, Jerry said he was still doing just fine. "But my wife smells ghosts," he quipped. He and I smiled and looked over at Sandy.

"I am not crazy," she insisted.

"Of course not," I said. I asked her if she had noticed changes in the odor of any other things that she smelled—foods, other people's breath. She shook her head vigorously before I was even done asking the question. "No. It's not me. I checked." She went on to tell me that she'd had Jerry take an over-the-counter ulcer medication for a week in case a stomach problem was the cause, but it hadn't made any difference.

"Not surprising," I told her. "Halitosis almost never arises from the

H. Lee Kagan is an internist in Los Angeles. The cases described in Vital Signs are real, but names and certain details have been changed.

esophagus, stomach, or intestine." Undaunted, she repeated, "Something's wrong."

I thought for a moment and then said: "Fair enough. You know, sometimes conditions in the lungs can cause the breath to be bad. Let's do a chest X-ray." Even though I was certain that the yield on the X-ray would be small, I wanted to be able to tell her we had turned over every stone in search of the cause of Jerry's nonproblem.

So even though Sandy was the only one who thought her husband's breath was bad; even though Jerry had no symptoms, findings, or risk factors whatsoever; and even though his lungs had sounded clear when I listened to them at his first visit, I had my medical assistant walk him down the hall for the chest film.

LOUIE PSIHOYOS/CORBIS

Odor specialists at Hill Top Research in Cincinnati investigate the subtleties of male breath.

SEVERAL MINUTES LATER MY ASSISTANT put the X-ray up on the view box in my office. I took one look and had to suppress an expletive. Sitting in Jerry's right midlung was a rounded density with a central cavity containing air and fluid. It was the radiographic signature of an abscess.

Amazingly, Jerry had been harboring a chronic infection in his right lung, but it had not been accompanied by any of the typical symptoms of an abscess—fever, cough, sputum production, sweats, and weight loss. He'd had none of them. None, that is, except for an odor on his breath. The smell of purulent sputum incubating deep within a lung may waft its way up the bronchial tree, resulting in serious halitosis. But in Jerry's case the odor was so subtle that it took the exquisitely sensitive olfactory memory of his wife to pick up the change. The "ghosts" she smelled were real, and antibiotics were exactly what it was going to take to get rid of them.

Adding to my surprise was the fact that Jerry had none of the risk factors associated with a lung abscess. Among patients with intact immune systems (not compromised by HIV or chemotherapy, for example), lung abscesses occur most frequently in those with conditions that impair the swallowing mechanism and allow for the aspiration of food or saliva into the lungs. Disorders such as strokes or neurodegenerative disease and conditions that depress consciousness like alcoholism, seizures, and drug abuse can all predispose to oral contents "going down the wrong pipe." When coupled with poor dental hygiene, which can lead to the buildup of bacteria, these disorders set people up for aspiration pneumonias, infections that can smolder and destroy normal lung tissue, literally rotting out a "dead zone" in the lung.

But in a small number of cases, lung abscesses may arise in the absence of any identifiable risk factor. It is possible that Jerry had a congenital anomaly in his bronchial tree that led to the pooling of mucus, and eventually to infection, but it is impossible to know for certain.

In the pre-antibiotic era, lung abscesses were fatal one-third of the time and left another third with lifelong debilitating lung disease. The introduction of lobectomy, the surgical removal of part of the lung, improved these numbers, but an extended course of antibiotics long ago replaced surgery as the mainstay of treatment for these infections.

In consultation with an infectious-disease expert, I started Jerry on clindamycin, a potent antibiotic effective against the anaerobic (non-oxygen-consuming) bacteria that most frequently populate this type of infected cavity. After six weeks, an X-ray showed the abscess had shrunk down to a stable and probably permanent scar on Jerry's lung. There was no reason to expect any recurrence. But had Jerry's abscess gone undiagnosed, it might well have continued to grow and could have eventually necessitated the surgical removal of part of his lung.

At a visit shortly after finishing the antibiotic course, Jerry told me he had gained new respect for both his wife's dogged persistence and her uniquely talented nose. Then he said he was considering adding a bit to his stand-up routine about hiring his wife out to the bomb squad at the Los Angeles International Airport.

"Or," I suggested, "maybe you could just get her a bouquet of sweet-smelling flowers and take her out to a nice dinner."

BY CARL ZIMMER

Fast driving, drugs, and unsafe sex: The risk-loving behavior of teenagers may result from a neurological gap in the developing brain.

TEENAGERS ARE A PUZZLE, AND NOT JUST TO THEIR PARENTS. WHEN KIDS pass from childhood to adolescence their mortality rate doubles, despite the fact that teenagers are stronger and faster than children as well as more resistant to disease. Parents and scientists alike abound with explanations. It is tempting to put it down to plain stupidity: Teenagers have not yet learned how to make good choices. But that is simply not true. Psychologists have found that teenagers are about as adept as adults at recognizing the risks of dangerous behavior. Something else is at work.

Scientists are finally figuring out what that "something" is. Our brains have networks of neurons that weigh the costs and benefits of potential actions. Together these networks calculate how valuable things are and how far we'll go to get them, making judgments in hundredths of a second, far from our conscious awareness. Recent research reveals that teen brains go awry because they weigh those consequences in peculiar ways.

Some of the most telling insight into the adolescent mind comes not from humans but from rats. Around seven weeks after birth, rats hit puberty and begin to act a lot like human teens. They start spending less time with their parents and more with other adolescent rats; they become more curious about new experiences and increasingly explore their world. Teenage rats also develop new desires. It's not just that they get interested in sex but also that their landscape of pleasure goes through an upheaval.

MIRIAM SCHNEIDER, A BEHAVioral pharmacologist who studies adolescence at the University of Heidelberg, and her colleagues recently documented this shift. The scientists ran an experiment on a group of rats of varying ages, allowing the animals to drink as much sweetened condensed milk as they wanted. The amount of milk they drank, relative to their body weight, stayed fairly constant through their prepubescent youth. But when they hit puberty, they started to drink much more. Once they became adult rats, their rate of milk drinking dropped and then stayed steady as they got older.

To any parent who has observed a teenager guzzle a bottle of soda, this spike would look awfully familiar. But the behavior of adolescent rats is not simply the result of their being bigger than juveniles. Schneider and her colleagues trained their rats to press a lever in order to get a squirt of milk. The rats had to press the lever dozens of times before they were rewarded with a single sip, and each successive sip required two more presses than the previous one. This requirement allowed Schneider and her colleagues to measure just how much work the rats were willing to put in for a reward. They found that pubescent rats would press the lever much more often than rats of any other age, putting in far more work for the calories they were getting, given their size. In other words, they valued the milk more.

A number of other experiments support Schneider's results. Whether rodent or human, adolescence makes us add more value not only to sweet drinks but to all sorts of rewards. A team led by Elizabeth Cauffman, a research psychologist at the University of California, Irvine, who studies antisocial behavior in adolescents, documented this shift with a game of cards. She and her team had volunteers play a simple gambling game with pictures of four decks of cards on a computer screen. At each turn of the game, an arrow pointed to one of the decks. The volunteers could either turn over a card or pass. Each card had a different amount of money on it—"+$100," for example, or "-$25." The goal of the game was to win as much of the imaginary money as possible.

The scientists had stacked the decks. Two of the decks had more losing cards than winning ones, and the reverse was true for the other two decks. When people play these games, they unconsciously shift their strategies as they see more cards. They pass more on some decks and take more cards from others. Cauffman and her colleagues tracked the strategies of 901 volunteers ranging in age from 10 to 30 years old and compared the teenagers with the other age groups. Across all ages, the older the volunteers were, the more they shied away from using the losing decks. But the scientists found a dif-

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ferent pattern when it came to the winning decks. Adolescents tended to play the winning decks more often than adults or preteens. In other words, they were unusually sensitive to the reward of winning money but the same as others when it came to the risk of losing it.

Underlying this behavior are the neural circuits of the teen brain. Neuroscientist B. J. Casey and her colleagues at the Sackler Institute of the Weill Cornell Medical College believe the unique way adolescents place value on things can be explained by a biological oddity. Within our reward circuitry we have two separate systems, one for calculating the value of rewards and another for assessing the risks involved in getting them. And they don't always work together very well.

Casey has tracked the workings of those dual systems by having volunteers play a game while lying in an fMRI scanner. She and postdoctoral fellow Leah Somerville showed 62 volunteers a series of smiling or calm faces. In some trials the volunteers had to press a button whenever they saw a smiling face; in other trials they were asked to resist the happy faces and instead respond to the calm ones, even though the sight of a happy face summons up the same reward-seeking responses in the brain as the sight of a dollar sign or the prospect of tasty food.

Casey tallied up how often the volunteers correctly responded to the calm faces, and how often they failed to resist the urge to press the button when viewing happy ones. Then she examined the brain scans of her subjects to see which areas of the brain became active and to see whether the age of the volunteers—ranging from 6 to 29—made a difference in their responses. Once again, the teens stood out from the others. When asked to press a button for calm faces, they became much more likely to mistakenly press the button for happy faces, too. In other words, the reward of a happy face made it harder for them to control their impulses.

The brain scans revealed how they were processing rewards differently. In teenagers only, the sight of a happy face triggered a significant response from the ventral striatum, a small patch of neurons located near the center of the brain. The ventral striatum is especially sensitive to dopamine, which produces a feeling of anticipation and helps the brain focus on reaching a goal. The ventral striatum produces bigger responses to bigger rewards, and in teens it is rigged up to an amplifier, making rewards seem more appealing still.

A separate network of regions in the front of the brain is responsible for evaluating conflicting impulses. This cognitive control network allows us to hold back an action that could deliver a short-term reward if it interferes with a long-term goal. The network grows very slowly over the first 25 years of life. As a result, it works poorly in childhood, better in teens, and even better in adults.

Casey was able to watch the cognitive control network in action. She and her colleagues analyzed the brain scans of volunteers while they kept themselves from hitting a key that they weren't supposed to hit. At those moments, part of the cognitive control network, called the inferior frontal gyrus, was more active than it was at other times. When the scientists compared the cognitive control network response in people of different ages, they found a striking pattern. In children the network was the most active, in teenagers the activity was lower, and in adults it was lower still. Casey proposes that as the cognitive control network matures, it gets more efficient. The upshot is that as we age, we need to put less effort into holding ourselves back.

THE TROUBLE WITH TEENS, Casey suspects, is that they fall into a neurological gap. The rush of hormones at puberty helps drive the reward-system network toward maturity, but those hormones do nothing to speed up the cognitive control network. Instead, cognitive control slowly matures through childhood, adolescence, and into early adulthood. Until it catches up, teenagers are stuck with strong responses to rewards without much of a compensating response to the associated risks.

> The human brain may be designed to help adolescents face the risks that come with a new stage of life. But modern dangers have increased those risks.

From an evolutionary point of view, the daredevil impulses of adolescents can be beneficial, Casey points out. Once a young mammal becomes sexually mature, it needs to leave its parents and strike out on its own. It must find its own supply of food and establish its place in the world of adults. In some mammal species, adolescence is a time for individuals to leave one group and find a new one. In others, it is a time to seek out sexual partners.

The reward system of the teenage brain may make adolescents more willing to face the risks that come with this daunting new stage of life. But with access to modern dangers like illegal drugs and fast cars, the human risks have increased. Evolution does not operate quickly enough to have reacted to such factors.

The brain's heightened responses can also open the way for psychological troubles. Due to experience, environment, or genes, some teens may possess relatively low levels of cognitive control, making them particularly vulnerable to neurological signals of fear, Casey suggests. If the signals go unchecked, they may lead to anxiety, depression, or other disorders such as addiction.

And even well-adjusted adolescents may be primed to choose the heart over the head—or, perhaps we should now say, the ventral striatum over the inferior frontal gyrus.

BY DAVA SOBEL

Lightning literally comes like a bolt out of nowhere. So scientists are setting up camp to decode the elusive physics of the flashes.

TITUSVILLE, FLORIDA—THE IDEAL SPOT FOR LAUNCHING SPACECRAFT in the United States just happens to lie right in the middle of a region known as Lightning Alley. Even when the air over Florida's Cape Canaveral—home to the Kennedy Space Center (KSC)—is free of storms, electrical conditions can cancel a liftoff. Flight controllers dare not send a rocket into a charged blue sky, where the craft might act as a giant, flying lightning rod. And before liftoff, an ill-timed bolt could easily scuttle a mission. "If lightning strikes near a vehicle being readied on the launchpad, we might have to retest every system to see if induced currents have caused damage," says Frank Merceret, research director of the space center's weather office. "We might even have to roll the space shuttle back into the Vehicle Assembly Building."

For all these reasons, Merceret eagerly welcomes the visit of two veteran researchers from the University of Mississippi, Tom Marshall and Maribeth Stolzenburg, whose ongoing project here seeks to explore fundamental lightning physics. Marshall says, "There's no lab analog for lightning." This is why his team has packed two van-loads of equipment for deployment here at the peak of summer's thunderstorm activity. Lightning is all too well-known for the way it conducts a potent rush of charge from agitated storm clouds down to ground level, but despite decades of research, the most important details of the dynamic still defy description. No one knows exactly how strokes begin—or "initiate" in lightning parlance—nor is it understood how they propagate within a cloud or from one cloud to another, or trace their jagged, stepped paths through the air from cloud to ground.

Marshall and Stolzenburg hope to capture the entire life cycle of a lightning flash by linking their custom-designed detectors to four other types of sensors, three of which are already permanent fixtures of KSC's lightning-warning system. Each type of sensor detects a different electromagnetic frequency, tuning in to a specific phase of the lightning stroke. Combining the inputs from all the sensors on microsecond timescales—something that has never been done before—will allow the researchers to capture a stroke as it ignites, accelerates, and moves charge.

They hope the data will eventually help shape a general theory of lightning behavior. As a more immediate, practical goal, Marshall and Stolzenburg want to test whether KSC's surveillance system reliably registers all the strokes thrown down during any given storm. Evidence from earlier studies suggests that some strokes slip by unnoticed during moments when sensors are overloaded.

Although the object of the scientists' study embodies beauty and terror in equal portions, the labor of their measurement entails many mundane duties: lugging car batteries to and from equipment installations, recharging them overnight, and repeating the process daily over a period of weeks. Today's site inspection takes us first to Merritt Island National Wildlife Refuge, on the fringes of the space center. En route we encounter several large swaths of vegetation smoldering in prescribed burns—fires set by the U.S. Fish and Wildlife Service to clear undergrowth or control insect pests. The lightning researchers view the patches of scorched ground through the hopeful lens of their interest: Perhaps the cloud of smoke from the burn will trigger lightning strikes. But this does not happen.

The Merritt Island lightning detection apparatus is housed in a large yellow metal locker with two antennas sticking up like high-hat cymbals on a drum set, and a sign warning "Danger High Voltage." One antenna is "fast," the other "slow." Both measure the amount of charge in a single event. Fast and slow are relative terms here, since everything about lightning happens quickly: The fast antenna (operating at 500 kHz) examines the field on a microsecond scale, while the lower-frequency slow antenna (running at 10 kHz) detects surges on a millisecond scale.

University of Mississippi graduate student Sumadhe Karanarathne, who built much of the equipment and wrote some of the computer code for it, unlocks the yellow box and downloads yesterday's data onto a portable hard drive (which he will take to the motel and back up four times, just to be sure he doesn't lose any of it to some unexpected glitch). His wife, Nadee, an engineer, rubs the surfaces of the attached antennas with alcohol wipes to remove conducting materials such as salt, dust, and spiderwebs. Undergraduate Lauren Vickers, who changed her major to physics after getting a taste of lightning research two years ago, swaps out a run-down pair of batteries for freshly charged replacements.

Near the Mississippi equipment box stands one of 30 instruments—small white canisters slung from

Dava Sobel, the author of *Longitude, Galileo's Daughter,* and *The Planets,* loves to watch scientists at work and write about what they do when they are "doing research."

SEAN KAUFMANN/GETTY IMAGES

tripods—in KSC's permanently installed Field Mill Network. These are arranged around the grounds to detect the surface electric fields that emerge when lightning is imminent. A separate KSC setup, the Cloud-to-Ground Lightning Surveillance System, records lightning as it hits the ground. For earlier warning, the space center's Lightning Detection and Ranging System tracks short surges of lightning in the clouds, up to 100 nautical miles away.

Our next stop is the nearby Space Coast Regional Airport, to check one of the seven receivers that the team has borrowed from the European LINET ("lightning network") and installed over a 3,000-square-mile area. Each of these receivers resembles a skeletal globe formed by two intersecting copper loops mounted together on an aluminum block. Pooled data from all seven should locate lightning surges measuring 1,000 to 10,000 meters long. Since reliable readings depend on perfect alignment, Stolzenburg sets a carpenter's level on the receiver while Marshall tightens a few bolts.

Before reaching under the wooden steps to check the cables that snake into the building where the data are recorded, the Mississippi researchers bend down and look around for real coral snakes that might be hiding there. Everything seems in order, so we move on.

As we drive, the researchers scan the sky for cloud activity, as though praying for rain. In fact, I'm certain they *are* praying for rain. By 11 a.m. a dark gray wall rising in the south looks promising to me, but I'm told those clouds are too shallow to produce a thunderstorm. An hour later, though, the clouds loom darker and larger, becoming real contenders. "We've done our work for the day," Stolzenburg says. "Now we just have to wait for the clouds to cook." She studies them again. "Probably after 2 p.m."

We return to the motel well before then. Once a storm breaks, the instruments function automatically, and a person had better observe from indoors. Lightning claims more lives in the United States than tornadoes, hurricanes, or winter storms. In a typical year, as many as 60 Americans are killed by lightning, and over 300 more are injured.

When the action starts—practically on cue, at 2:50 p.m.—Marshall and Stolzenburg turn out to have the room with the best view of the mayhem. They invite me to watch with them. "Those CG [cloud-to-ground] strikes behave differently from the IC [intracloud] lightning," Marshall says, offering play-by-play commentary. Stolzenburg, meanwhile, has an eye on the Web site displaying the space center's real-time radar. From her perspective, the true beauty of the storm outside the window is the number of strikes—17 so far—it has delivered near the team's sensors.

There will be lots of data to download tomorrow. Refining the theory of lightning lies in the weeks and months ahead.

Lightning makes a two-pronged touchdown from a cloud over Mobile, Alabama. The complex dynamics of such bolts are poorly understood.

iPads, 3-D TVs, and other slick modern displays ignore one critical shortcoming: the fact that we need screens at all.

BY DAVID H. FREEDMAN

OVER THE PAST FEW YEARS, I'VE DEVELOPED TWO HABITS THAT HAVE made me an increasingly unpopular movie date. One is a strong preference for 3-D movies, undeterred by low artistic value or by sensations commonly associated with brain tumors and food poisoning, not to mention the big, dorky, blinking plastic glasses. (I can't wait to upgrade my home TV to 3-D—my family, bless them, having assured me that blinking glasses are the least of my problems when it comes to looking dorky.) The other is that I've come to like sitting ever closer to the theater screen, advancing at the rate of approximately one row every six months.

See, I'm trying to go beyond watching movies to being inside movies. I don't get why everyone doesn't feel this way. People make a big deal about how big and bright and sharp the iPad screen is. Well, sure, compared with the murky, teeny phone screens we all spend half our lives peering at. But compared with real life, it's still a pretty murky, teeny screen, and one that imprisons flat images. If you find watching *Avatar* on an iPad an immersive experience, more iPower to you. As for me, when I'm in media-consumption mode, I want to experience the you-are-there feeling you get when you are, well, there. I want freedom from screens.

Researchers feel my pain, apparently, because some of them have been working on peeling video off glass displays so that filmed objects appear to hang out in the thin air around us. There's a long way to go, but a reasonable first step toward fully immersive 3-D entertainment would be better, less nauseating 3-D effects. The essential ingredient of a 3-D image is stereoscopic photography, in which each eye receives an image representing a view from a slightly different angle. A simple way to achieve this is to develop two screens, one for each eye. You could probably go to Brookstone and get thick glasses lensed with individual TV screens, but that would be taking you in the wrong direction, dorkiness-wise. Nanobiotechnologist Babak Parviz and his team at the University of Washington are developing a much cooler approach: display screens built into contact lenses.

Transforming televisions into contact lenses turns out to be a difficult feat even in our age of microminiaturization. The list of problems is impressive. First, it requires microlenses that sit on top of the main lens to properly focus images. It needs a way to adhere electrical components to the lenses without distorting picture quality. It needs a power source. (Parviz is experimenting with wireless radio-frequency energy.) And all this must happen on 1.5 square centimeters of polymer that's transparent, flexible, nonirritating, fluid-friendly, and free of all the toxic materials normally used in glowing microelectronic components. As Parviz says, "It's a pretty intricate optical system for a contact lens."

He has come close to solving every one of these problems. His prototype contact lenses do not seem to ruffle the rabbits that have worn them. Granted, these test subjects have not yet been subjected to actual television; so far Parviz has managed to incorporate just a single blinking LED on the lens. Then again, you'd be surprised how much information a single dot can deliver. Imagine a lens that blinks to notify the hearing-impaired of an incoming call or to signal you when your mother-in-law is pulling into the driveway. Video lenses are inestimably far off, Parviz concedes, but in the next few years he expects to build contacts with preprinted, illuminable characters and icons as well as an eight-by-eight array of LEDs. If networked, even a rudimentary display could deliver useful visual cues, such as turn signals from your GPS so you can keep your eyes on the road.

BUT A SCREEN IS STILL A SCREEN even if it's plastered to your eyeballs. What I really want is to ditch solid displays altogether and see images popping out in thin air. As it happens, thin air may be fine for breathing, but it's a lousy medium for image projection; there's very little to bounce light off, let alone a way to control how it bounces to make sure it finds its way into your eye. Thick, humid air turns out to be a different story, though, and nothing thickens air so reliably (as anyone in London or San Francisco could tell you) as water vapor. Conveniently, water can both reflect and transmit light, a property known as transflection. A company called FogScreen in Helsinki, Finland, has figured out how to take advantage of all these facts to project fairly crisp, bright images onto—yes—a screen of fog. FogScreen's machine enlists an array of tiny nozzles to spit out row after row of near-microscopic drops of water, forming a thick slab of fog onto which a projector can shine a surprisingly bright, clear image.

The advantage of a screen made of more or less nothing is that you can direct any part of your body right through it without the usual

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side effects of entering glass. Like regular fog, FogScreen fog doesn't even feel wet. If the motivation for punching through a display seems elusive, think about all the prime image-display space around you that has too much foot traffic for a conventional screen: hallways, sidewalks, doorways, and the area smack in the middle of your living room, your office, or a mall shop. That's why we put computer monitors, TVs, and other electronic displays near walls, on furniture, up above our heads, or in our hands: so we won't bang into them. An immaterial screen removes this arbitrary limitation. For six years now, FogScreen has been installing its technology in clubs, concert halls, and shopping areas as a kicky way to flash images or get a message across right under the noses—indeed, right up the noses—of people who are free to plow right on through the image.

FogScreen's two-dimensional floating displays are fine as static billboards, but the technology is not yet suited for watching movies or updating your Facebook status. The reason is simple: Turbulence—or laminar airflow, as FogScreen engineers like to call it—gets in the way. The tiniest eddies in air send ripples through the fog, rendering the slab too bumpy and jittery to support images detailed enough for watching sharp video or reading text. "I don't see these screens coming to homes next year," says Ismo Rakkolainen, the user-interface scientist at the University of Tampere in Finland who coinvented the fog-display technology. On a more hopeful note, Rakkolainen adds that it should in coming years be possible to create thicker slabs of image-embellished fog that can be made to resemble 3-D objects. "It could be the first technology that comes close to the *Star Wars* holographic images."

Now we're talking. Rakkolainen is referring to the iconic Princess Leia hologram that emerges from R2-D2's navel and other holographic projections like it in the *Star Wars* movies, only actual holography requires no wispy clouds of moisture. A hologram is an image most easily created when two beams of laser light are reflected from an object or scene onto some sort of light-sensitive film or plate. The beams of light cancel out in some spots on the plate and reinforce each other in other spots, creating a distinctive "interference pattern" that imprints on the plate. When laser light is later shone through the interference pattern, the object or scene appears to float in space with sharp, vivid realness that can be hard to distinguish from real realness. You can even view the object from different angles as you move your head or walk around it—no dorky glasses required.

VIDEO HOLOGRAMS ARE A BEAR, HOWEVER, because they require recording an interference pattern in all its incredible detail while the pattern is constantly changing. Fancy computer tricks have proved dead ends, but researchers at the University of Arizona may be onto something with a novel organic polymer known as PATPD/CAAN:FDCST:ECZ:PCBM. (You can drag the full name out of Google on your own time.) A sheet of PATPD-etc. will faithfully record a single interference pattern, just like a photographic plate. But PATPD-so-forth's big trick is that it can erase the pattern, almost Etch A Sketch style, and immediately record a new one, creating a moving image one frame at a time. It has taken University of Arizona physicist Pierre-Alexandre Blanche and colleagues some 15 years to come up with a film that faithfully records sharp patterns and quickly auto-fades. "We tested thousands and thousands of different formulations, always looking for any tiny improvement we could get," Blanche says. "Over time we've improved the sensitivity by a factor of 100." Sadly both for him and for us Princess Leiagram fans, his work is far from over: The film currently requires lasers powerful enough to take down your neighbor's TV, and it can show only two frames a second, far from the 30 frames per second needed for video. Part of the performance leap required for a commercial version could be covered by new generations of more efficient lasers already hitting the market, but the film still needs to be several times more sensitive. "It won't be in Walmart in two years," Blanche says. "Maybe 10."

Perfect by me. That's just when my 3-D TV will be ready for an upgrade, and I'll be first in line for that system.

Then Blanche got me thinking about the ultimate kind of immersion. Would it be possible to create interference patterns in thin air so that we could have holographic images all around us without having to risk banging into plates of PATPD-whatever? Or if not thin air, how about thick air?

Sure enough, FogScreen's chief technology officer, Arttu Laitinen, says his company has been closely following developments in the field of holography with an eye to creating interference patterns on fog. Laitinen adds that a commercial product along those lines is just a glimmer on the event horizon at this point, but just think: floating, screenless images that you can walk around right in the middle of your room. I absolutely intend to upgrade my personal robot with that capability as soon as my starship makes port.

SCOTT BAKAL

Inside...

The Ecosystem

The trillions of microbes that live in the human gut could be the key to fighting disease without antibiotics.

By Michael Tennesen

IN THE INTENSIVE CARE NURSERY AT DUKE UNIVERSITY MEDICAL Center, doctors and nurses attend to premature infants in rows of incubators surrounded by ventilators and monitors. As new parents holding packages of breast milk watch their tiny babies, neonatologist Susan LaTuga makes her rounds, checking vital signs and evaluating how the infants tolerate feeding. She consults with nurses, dietitians, and pharmacists about the course of the day's treatment for the babies, some of whom weigh as little as one pound and were born as much as 17 weeks early.

At the end of her shift, LaTuga stops at a freezer and inspects stool samples from some of the infants that are at the center of a remarkable new study. Across the Duke campus, technicians are waiting to analyze them with a powerful gene sequencer capable of penetrating the hidden world of the billions of microorganisms growing inside each infant.

LaTuga is one of several medical researchers at Duke working

with microbial ecologists to study the development of the human microbiome—the enormous population of microbes, including bacteria, fungi, and viruses, that live in the human body, predominantly in the gut. There are 20 times as many of these microbes as there are cells in the body, up to 200 trillion in an adult, and each of us hosts at least 1,000 different species. Seen through the prism of the microbiome, a person is not so much an individual human body as a superorganism made up of diverse ecosystems, each teeming with microscopic creatures that are essential to our well-being. "Our hope is that if we can understand the normal microbial communities of healthy babies, then we can manipulate unhealthy ones," LaTuga says.

The Duke study is just one of many projects begun in the past five years that use genetic sequencing to explore how the diversity of the microbiome impacts our health. Two of the largest efforts are the Human Microbiome Project, funded by the National Institutes of Health (See "Your Microbial Menagerie," opposite), and the European Union's Metagenomics of the Human Intestinal Tract. Although these groups have only just begun to publish their findings, it is already clear that the microbiome is much more complex and very likely more critical to human health than anyone suspected. Understanding and controlling the diversity of our germs, as opposed to assaulting them with antibiotics, could be the key to a range of future medical treatments.

IN-DEPTH ANALYSIS OF THE HUMAN BODY'S MICROFLORA HAS BEEN possible only in the past few years—a by-product of the same new gene sequencing techniques that have allowed scientists to cheaply and accurately identify the DNA of the human genome. "Gene sequencing has opened a huge door to how complex these communities are," says Patrick Seed, a Duke pediatrician specializing in infectious disease, who with biologist Rob Jackson is a lead investigator of the premature infant study.

Before sequencing was available at a reasonable price, microbes were identified by growing them in a petri dish. But "not all microbes will grow in culture," LaTuga says. "It identifies only about 20 percent of the microbes in the gut."

Like a lush rain forest, a healthy microbiome in the human gut is a diverse ecosystem that thrives only when all the interdependent species are healthy too. "In an ecological sense, more diverse communities are healthy on land and in the seas," Jackson says. "No one species is dominant, and the ecosystem is more productive and resistant to major changes." The comparison is more than just a convenient analogy. Jackson was studying microbial communities around the world, including in the Amazon, when he realized that the ecological balance in those environments was not so different from the balance present in a healthy human gut. (One of his more counterintuitive findings is that microbial communities are more biodiverse in the American Plains than in the Amazon rain forest.)

Jackson's work on microbial diversity caught the attention of Seed, who was already interested in the microbiome in the guts of preterm infants but who did not have a background in ecology. He sought out Jackson, and the two decided to collaborate on what they call the Preemie Microbiome Project. The Duke medical researchers and ecologists who have joined that project hope to identify which species flourish in early stages of the human microbiome, how they are influenced by the consumption of breast milk, and what role they play in critical diseases affecting infants as well as in chronic diseases that occur later in life.

"The classical view of infectious disease is that a single organism invades and produces an infection," Seed says. "But then we found that certain diseases, like irritable bowel syndrome, seem to be caused by imbalances in the organisms that communicate with the host. So then people asked, 'Why is this not the case for many other states of human health?'" Preliminary work by other groups, similarly made up of both biomedical researchers and microbial ecologists, suggests that imbalances in the microbiome might also be linked to allergies, diabetes, and obesity.

The partnership between ecologists and biomedical researchers is characteristic of how things work in the relatively new but burgeoning field of microbiome studies. Vanja Klepac-Ceraj, a microbial ecologist by training and an assistant research investigator at the Forsyth Institute in Cambridge, Massachusetts, has helped organize symposia with ecologists and biomedical researchers giving joint talks on the ecology of disease. "Biomedical scientists understand disease, so they know where the problem lies within the body," she says. "Ecologists understand complex systems and the interaction of many organisms."

Klepac-Ceraj recently worked with Michigan State University ecologist Brian Maurer on a study of cystic fibrosis that showed the importance of microbial biodiversity in diseased lungs. Cystic fibrosis leads to mucus buildup in the lungs, which creates habitats for microbes and ultimately makes patients prone to lung infections. But their study of 45 cystic fibrosis patients showed that when the respiratory tract contains a more diverse community of microbes, the patient is less likely to harbor *Pseudomonas aeruginosa,* a key pathogen associated with later stages of cystic fibrosis. "The fuller and more diverse community correlated with a healthier outcome even though that community was not the model of a healthy lung," Maurer says.

MICROBIOME STUDIES RUN DIRECTLY AGAINST THE NOTION IN THE minds of most people—even many researchers—that microbes are linked to disease, not to health. And of course not all microorganisms are benign. Infants in particular are susceptible to a number of diseases caused by gastrointestinal bacteria, including sepsis, chronic diarrhea, and necrotizing enterocolitis, an infection of the intestinal lining that is one of the leading causes of

Like a lush rain forest, a healthy microbiome in the human gut is a diverse ecosystem.

PAGE 34: MASTERFILE

Your **Microbial** Menagerie

Two hundred trillion microscopic organisms–bacteria, viruses, and fungi–are swarming inside you right now. The largest collection, weighing as much as four pounds in total, clings to your gut, but your skin also hosts more than a million microbes per square centimeter. One population thrives among the hair follicles on your scalp, while an entirely different one resides in the crook of your elbow. About 1,000 species can live in the human mouth, where different sides of the same tooth sustain distinctly different combinations of bugs.

Surprisingly little is known about these invisible communities and how they affect us. In 2007 the National Institutes of Health (NIH) launched the Human Microbiome Project, a $115 million initiative exploring the bugs that exist in the human body, whether people all share a core population of such organisms, and how changes in microbial ecosystems influence human health and disease. In 2009 NIH geneticist Julie Segre published a study showing that physiologically comparable parts of the body host similar microbial ecologies, whereas contrasting areas–say sweaty underarms and dry forearms–have drastically different communities. "My scalp community is much more similar to your scalp than to my own back. That's because bacteria thrive in particular environments," Segre says. For instance, she notes, the face is ideal for *Propionibacterium acnes,* a bug that thrives on the oily, waxy remains of dead cells. "People often associate *P. acnes* with acne problems, but it also breaks down oils into a natural moisturizer for the skin."

The notion that the human body is teeming with hidden life may seem creepy, but our resident microbes seem to be overwhelmingly harmless. They educate the immune system and outcompete and block potential pathogens. For instance, *Staphylococcus epidermidis,* which lives all over the skin, prevents deadly staph strains from taking hold. "It's remarkable how Americans are so focused on sterilizing our exterior using antimicrobial products," Segre says. "Bugs throughout the body keep us healthy. We need to lose some of that language of warfare." AMY BARTH

A common microbe living on human skin, *Staphylococcus aureus,* is usually harmless but can lead to serious infections.

DR. KARI LOUNATMAA/PHOTO RESEARCHERS

death in premature babies. Antibiotics have long been the first option in fighting these dangerous microbes, but many researchers are troubled by modern medicine's heavy reliance on them. After all, many pathogens found within the human microbiome are harmless or even beneficial. "There is *Staphylococcus* and *E. coli* in all of us, but they don't always cause problems," Jackson says. "It's the balance that is important. A more normal population of microbes in the gut can offset the bad players."

The Preemie Microbiome Project is an important step in understanding how we achieve a healthy, balanced microbiome in the first place. Researchers know that infants acquire about 100 species of microbes in the birth canal, and others come from the mother's skin after birth. As a child's contacts increase, some microbes are added from the doctor, the nurses, the proud dad, the doting relatives, and the curious family pets. By the time a baby is 6 months old, he or she has some 700 species of microflora, and by the end of the third year, each child has a microbial community as unique as a fingerprint.

Most of the infants enrolled in the Duke study are delivered by cesarean section, generally because the mother or the child has an infection or because the mother suffers from pregnancy-induced hypertension. Since they do not travel through the birth canal, "these infants come into life with virtually a clean slate, with few or no microbes at all," Seed says. "It gives us an opportunity to understand how the system works and develops."

The study also gives the researchers a chance to understand how antibiotics impact the formation of the microbiome. "Most premature infants are given antibiotics right away because of the dangers of disease," LaTuga says. "But more and more, we are learning antibiotics have multiple risks."

Heavy use of antibiotics can lead to antibiotic resistance, but researchers now speculate that antibiotics can also upset the balance of the microbial community, allowing disease to take over rather than fighting it. Michael Cotten, another neonatologist on the Duke project, analyzed the duration of antibiotic therapy given to 4,039 premature babies at 19 treatment centers across the country and found that prolonged use of the drugs is associated with increased risk of necrotizing enterocolitis and death. Antibiotics probably also prevent beneficial bacterial communities from forming in infants.

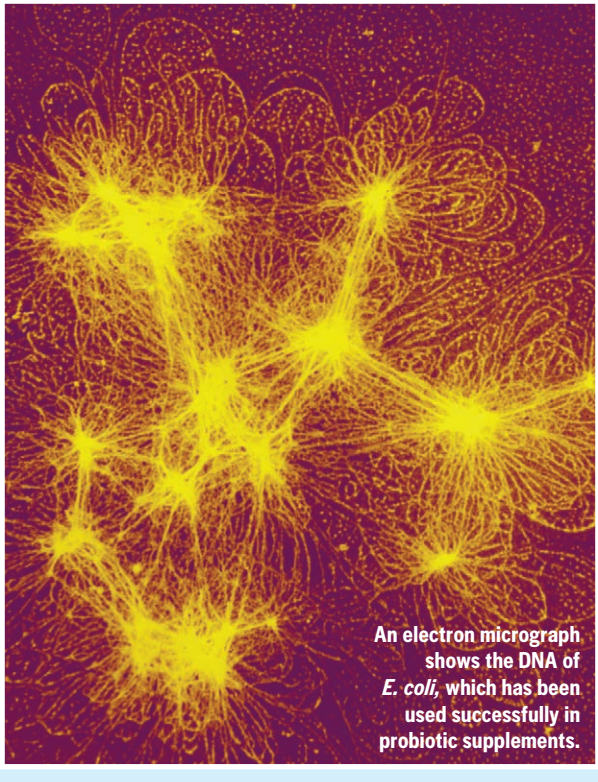
Last year, Stanford microbiologist David Relman published a study that illustrated the potentially devastating impact of antibiotics on the microbiome. He gave three healthy adults a five-day course of the antibiotic Cipro, then another course six months later, and monitored the state of the microbiome after each treatment. The gut flora of all three subjects gradually recovered from

Bugs **for** Breakfast

Around 9 million adults in the United States take "probiotic" supplements–pills packed with microorganisms such as *Lactobacillus acidophilus* and *Bifidobacterium lactis,* bacteria that are known to promote gut health. Foods containing microbial cultures, including yogurt, bear probiotic labels claiming they build immunity and improve digestion. Over the past five years, the U.S. probiotics business has grown almost 9 percent to about $5 billion a year, according to market research estimates.

But do probiotics actually improve the average person's health? Researchers are not sure. "A live yogurt with a few billion organisms sounds like a lot. But when you compare that with the trillions of organisms already in the body, it's a bit like throwing a packet of poppy seeds in a giant weed field and expecting to grow poppies," says Jeremy Nicholson, a biological chemist at Imperial College London. That said, Nicholson has found that some probiotics can have a dramatic impact. In 2008, when he fed *Lactobacillus* to mice with a transplanted human microbiome, he observed metabolic changes in the animals' gut, liver, kidneys, and parts of the brain. Yet Nicholson discovered that the animals' internal bacterial communities barely changed, suggesting that probiotics work by chemically signaling the microbes already living in the body, causing them to become more active.

Predicting the effect of probiotics on an individual is difficult. "A lot of them work in some people but not others because of differences in a person's biology, genetics, and environment," Nicholson says. There is no conclusive evidence that commercial probiotic pills and foods will benefit someone who is already in good health. But David Relman, a microbiologist at Stanford University, notes that malnutrition may limit the gut bacteria that help digest nutrients, exacerbating the impact of a poor diet. "Many kids in the developing world are not able to make efficient use of their food supply," he says. "A carefully constructed set of microbial strains could help them." **A. B.**



An electron micrograph shows the DNA of *E. coli,* which has been used successfully in probiotic supplements.

DR. ELENA KISELEVA/SCIENCE PHOTO LIBRARY

the impact of the antibiotic treatment but never returned to their original state—they had different compositions and were less diverse. "We don't know if these differences matter to health," Relman says. "But in general, you'd be concerned about a change." He had chosen Cipro because it has limited effectiveness against most species of bacteria in the gut, but it still affected one-third to one-half of the microbial flora in the subjects. "Knocking out one organism could have a ripple effect on the lives of others," Relman says.

This is especially concerning given that the number of different microbial species in the intestines may be important in countering pathogens. "The greater the diversity, the lower the probability that pathogens can invade and persist," says Richard Ostfeld, a disease ecologist at the Cary Institute of Ecosystem Studies in New York. "If all the niches are taken up in the gut, it might be hard for them to get hold."

Jackson puts it more bluntly. "When you use antibiotics, you are essentially dropping a bomb on a microbial community, hoping that your explosion will not harm anything useful," he says. "It's like setting a forest fire in order to control the weeds. What we're suggesting is to carefully manipulate the members of the community and the relationships between them, rather than wiping them out."

MANAGING THE MICROBIOME INSTEAD OF PUMMELING IT WITH antibiotics has produced impressive results in chicken and mice studies, pointing the way not just to future human treatments but also to a healthier food supply. For instance, increased use of antibiotics in chicken feed has led to an alarming growth of antibiotic-resistant bacteria in poultry. That resistance can get passed on to poultry consumers as well. In an effort to develop techniques to counter this worrisome trend, U.S. Department of Agriculture scientists introduced what they call a "competitive exclusion culture" of 29 different bacterial species into farm-raised chickens as part of their diet and then exposed them to salmonella. They found that chickens exposed to the bacterial culture had 99 percent less salmonella colonization than unexposed chickens.

In another animal microbiome experiment, Jeffrey Gordon, a biologist at Washington University in St. Louis, took a suite of microbes from the guts of both obese and lean mice and transplanted them into the guts of microbe-free mice. The mice that received the microbiomes of the obese mice gained significantly more weight than did the mice with the lean-mouse microbiomes. The results were the same regardless of whether the obesity of the donor mice was due to genetics or diet. Although caloric intake is still the most important factor in obesity, Gordon's research suggests that the microbiome may play a significant role by affecting the ability to extract energy from food and to deposit that energy as fat.

Researchers hope to achieve similarly dramatic results in humans next. A critical step in making this happen is deciphering how microbes communicate. "The establishment of healthy microbial communities almost certainly requires chemical messaging between the species present in the human host," says Texas A&M University biochemist Paul Straight, who studies interactions among bacteria. Microbes can use chemical signals, including small

When you use antibiotics, you essentially drop a bomb on a microbial community.

molecules, proteins, and DNA, to encourage neighboring organisms to grow or to tell them to stop growing. If researchers can capture and understand these molecular exchanges, they might be able to produce a kind of phrase book of chemical reactions. Such information could then be used to initiate this kind of molecular conversation on command, with an eye toward promoting the growth of helpful microbes or stunting harmful ones.

Specially packaged mixtures of microbes, known as probiotics, may also prove useful for balancing microbes in the gut (See "Bugs for Breakfast," opposite). Probiotics are now generally sold as health food supplements, and many of them are promoted as magic bullets that can improve metabolism or bolster immunity. Since they are as yet unregulated by the FDA, though, it is impossible for the consumer to know exactly what is inside; labels on over-the-counter products can be deceptive. Scientists who have tested them have often found something quite different from what the product promises. Nevertheless, carefully regulated probiotics, which introduce nonpathogenic competitors to disease, could be effective at balancing the gut microbiome.

THE RESEARCHERS ON THE PREEMIE MICROBIOME PROJECT ARE getting closer to understanding how we first acquire a healthy dose of inner microbes. They have finished sequencing the gut microbiomes of two groups of infants and have found that those infants are home to a surprising number of fungal species. Bacteria make up the vast majority of microbes in the adult body, so this finding suggests that fungi may play an unexpectedly important role both in the early development of microbial communities and in the health of infants.

Gene sequencing is also allowing Jackson and Seed to track down the sources of microbes, both benign and malignant, that find their way into the newborns in the study. They are uncovering evidence that mothers, breast milk, and hospital surfaces all contribute to the microbiome populations of infants. As part of this work, the researchers are linking pathogenic strains in the infants to specific instruments in hospital nurseries, information that could help doctors make the infamously contaminated hospital environment safer for vulnerable newborns.

The Duke team is also exploring whether the gut microbiome influences immune and metabolic development. If this turns out to be the case, it could be possible to introduce microbes that would improve infant immunity and metabolism. And the researchers are continuing to investigate the role breast milk plays in maintaining and encouraging the growth of a healthy gut microbiome. Breast milk is high in oligosaccharides, complex sugars that cannot be digested by the body but that may improve metabolism and immunity. By sampling the stool of premature infants and the stool and milk of their mothers, Seed and Jackson hope to understand how breast milk influences the timing of the appearance of different bacteria and fungi in the infant's guts.

Studies have shown that infants who are breast-fed are healthier, develop more quickly, and often have higher IQs. "We treat breast milk as a medication," says LaTuga, who believes that for now, breast milk is the best weapon doctors have to prevent infection in premature infants, reducing the need for long courses of antibiotics. "What is it that makes mother's milk so beneficial?" she asks. "How does it alter the gut microbiome to improve the healthy outcome of these babies? If we could answer those questions, we could help save infant lives."

The Duke group is still puzzling over how to translate their microbiome findings into practical treatments for premature infants. But at least one procedure that allows doctors to manipulate the gut microbiome is already here. A team led by University of Minnesota immunologist and gastroenterologist Alexander Khoruts has recently demonstrated spectacular success with fecal transplants, which introduce healthy stool microbes into a diseased bowel. An obscure and poorly understood procedure, it was first developed in the 1950s, well before anyone grasped the importance of the gut microbiome.

Khoruts and his colleagues reported last summer that they were able to use a fecal transplant to treat and apparently cure a woman with a life-threatening *Clostridium difficile* infection, which causes severe inflammation of the colon. The patient had an extremely poor prognosis: Suffering from chronic diarrhea, she had lost 60 pounds over eight months. "All antibiotics were failing, and she was in really bad shape," Khoruts says. In a last-ditch effort to improve her condition, he mixed a small sample of the patient's husband's stool with saline solution and injected it into her colon. Within 24 hours her diarrhea had stopped. After a few days, the symptoms were gone.

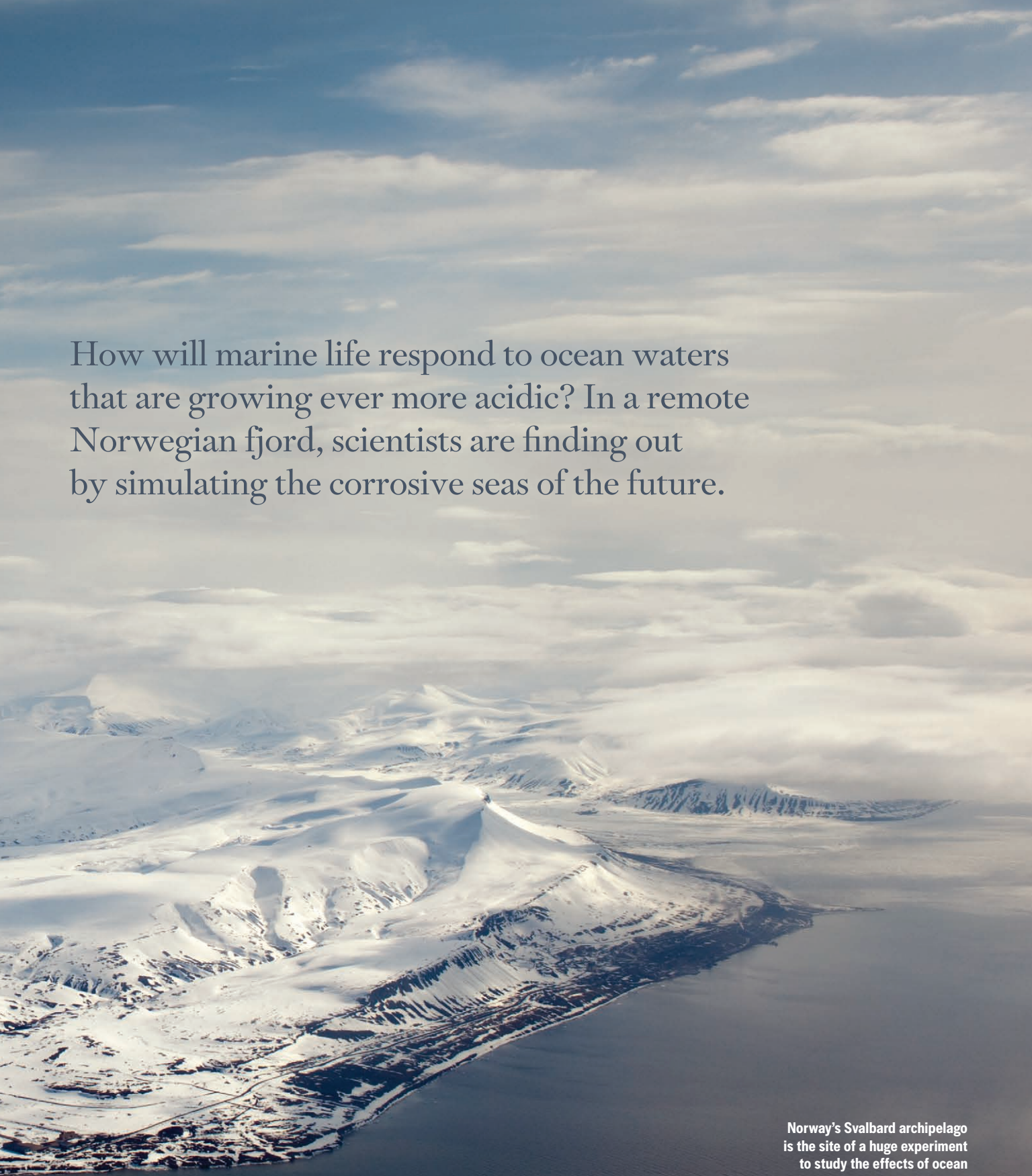
In studying this patient's progress, Khoruts was initially surprised to find that there was a nearly complete replacement of the woman's microbial flora with her husband's microbes. "By the time these patients get to this desperate treatment point, they've taken so many antibiotics that their microbiome has been decimated," he says. "So when we transplant the new bacteria, they simply move in to occupy the empty space." Before Khoruts and his team performed the procedure, no research had been done on how fecal transplants work or how they impact the microbiome. "Since then we've done another 23 patients," he reports, "all with dramatic stories."

As the cost of sequencing the human genome has plummeted in recent years, many medical researchers have touted the potential of personalized medicine—exotic therapies and synthetic drugs that are tailored to our individual genetic makeup. But "one day," Jackson says, "a genetic profile of our microbiome will be taken by doctors, with treatments prescribed from instant molecular data." The secret to keeping yourself healthy, it seems, might be to start by keeping your germs healthy.

the ocean acid test

PHOTOGRAPHY BY **NICK COBBING**

How will marine life respond to ocean waters that are growing ever more acidic? In a remote Norwegian fjord, scientists are finding out by simulating the corrosive seas of the future.



Norway's Svalbard archipelago is the site of a huge experiment to study the effects of ocean acidification on marine life. Rising levels of carbon dioxide in the atmosphere are making seawater corrosive to ocean organisms' skeletons and shells.

BY **JENNIFER BARONE**

This past summer, 35 oceanographers and marine biologists from Europe and Asia trekked to Norway's Spitsbergen island, about 750 miles from the North Pole. Then they kept going, right into the water, and set up an elaborate system of underwater test tubes. Their mission was to study how the abundant marine life in these frigid waters will bear up under the stress of one of the world's most daunting, if least publicized, environmental threats: the rising acidity of the oceans.

As carbon dioxide levels in the atmosphere increase, the seas absorb greater amounts of the gas, which reacts with water to form carbonic acid. Surface waters today are 30 percent more acidic, on average, than they were at the start of the Industrial Revolution. And unlike the storms, droughts, and heat waves that might be spawned by climate change—which are difficult to measure and predict—ocean acidification advances with disconcerting regularity. The most conservative models forecast that the ocean will be twice as acidic as in preindustrial times by the end of this century. "In the past 200 years, we have manipulated seawater chemistry at a rate that has not occurred for at least 20 million years," says oceanographer Jean-Pierre Gattuso, coordinator of the European Project on Ocean Acidification (EPOCA) and a lead scientist on the Spitsbergen experiments.

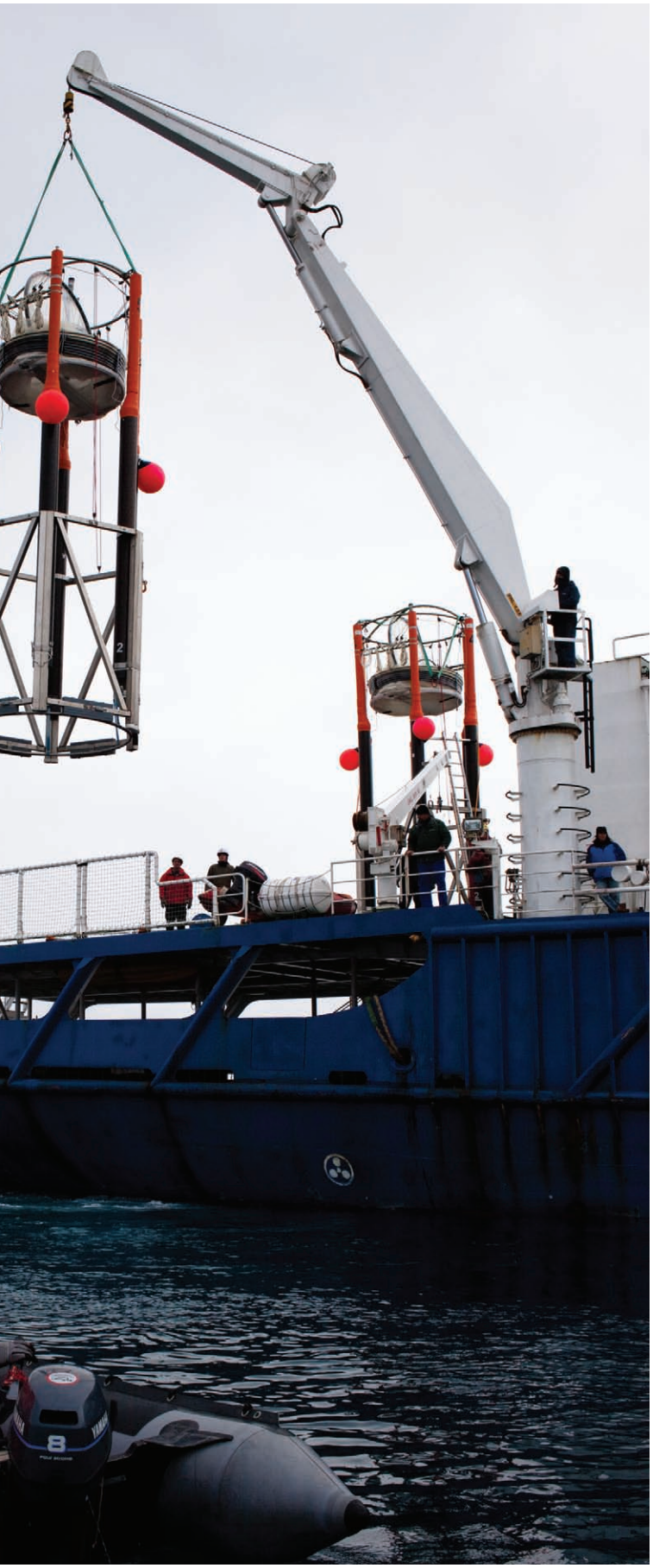
Previous episodes of acidification—possibly caused by CO_2 released from huge, sustained volcanic eruptions—had a tremendous ecological impact. "We know that past acidification events played a role in mass extinctions, when lots of animals and plants disappeared from the ocean," Gattuso says. "Life is flexible, so some organisms were able to adapt and evolve. The worry today is that the change is happening so fast that many may not have time to adjust."

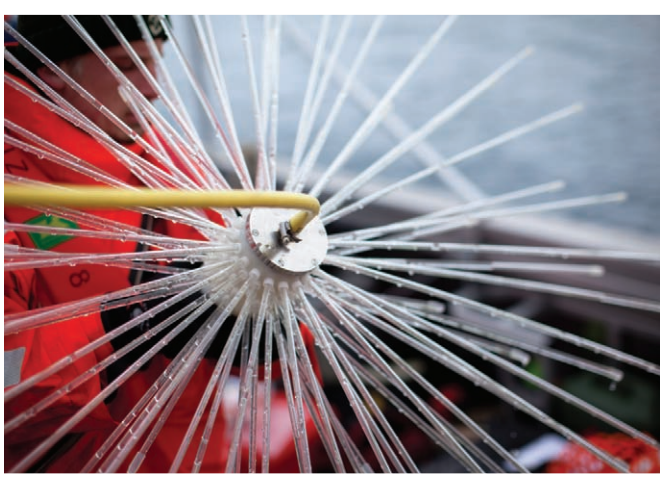
The science of how soured waters will affect marine life is still young, but the evidence so far suggests that the hardest hit will be organisms that have shells or skeletons built from calcium carbonate, including corals, mollusks, and many plankton. Acids dissolve carbonate, so as pH levels in the world's oceans drop, these animals may have trouble maintaining their body parts.

"The thing that's really unknown is how marine ecosystems will respond," says National Oceanic and Atmospheric Administration marine biologist Ned Cyr, who chairs a government task force that is developing a coordinated national plan to monitor the problem. "In the ocean, everything eats everything else. If we start losing key prey species, we may find ourselves with all kinds of unexpected effects."

Gattuso and his colleagues set up the Spitsbergen experiments to investigate those effects. In the largest study of its kind, the group has monitored the reaction of species at the base of the marine food web—viruses, bacteria, microscopic plants called phytoplankton, and their animal counterparts, zooplankton—to various degrees of acidity. The results will allow scientists to predict how ocean life will respond to CO_2 levels that have been projected to rise 40 percent over the next two decades.

A recent United Nations report cautions that with more than a billion people worldwide relying on seafood as their primary source of protein, acidification could pose a major threat to the human food supply. "The obvious solution to the potential threats posed by acidification," the authors say, "is to make rapid and substantial cuts to anthropogenic CO_2 emissions." Gattuso and his colleagues hope to find out how big and fast those cuts will have to be. "The goal," he says, "is to determine whether there is a tipping point that we do not want to reach."

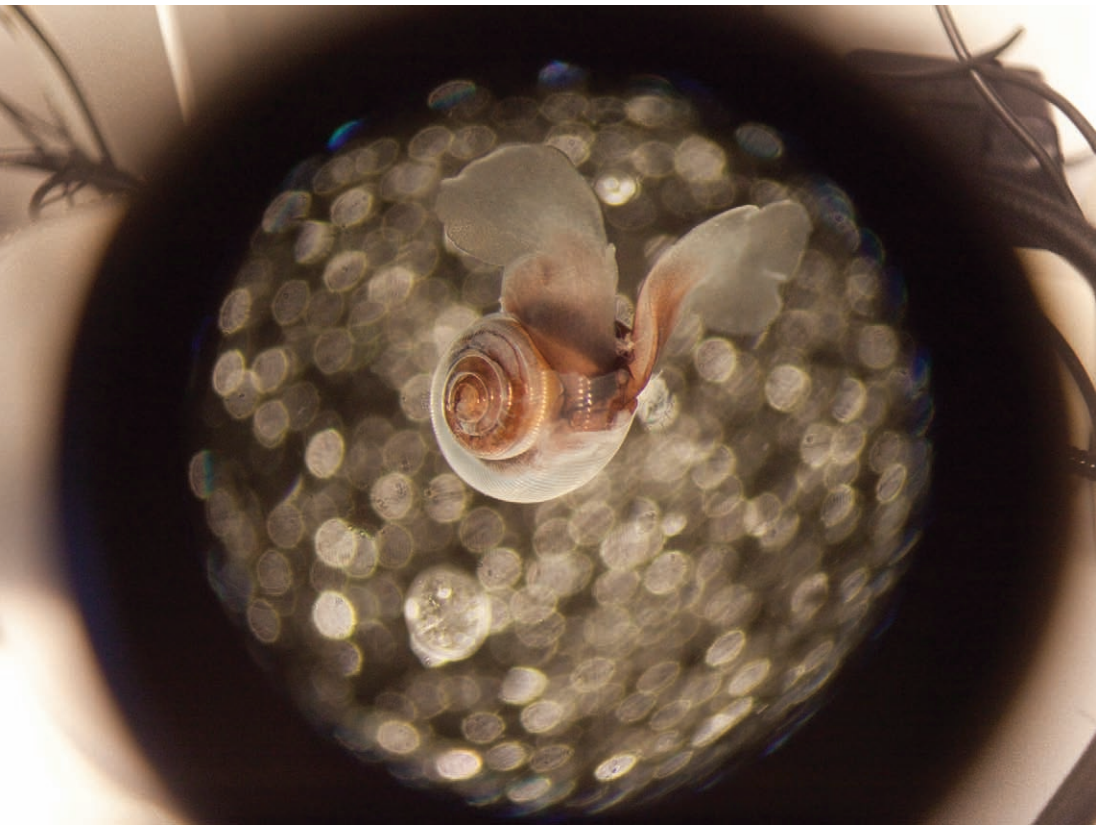




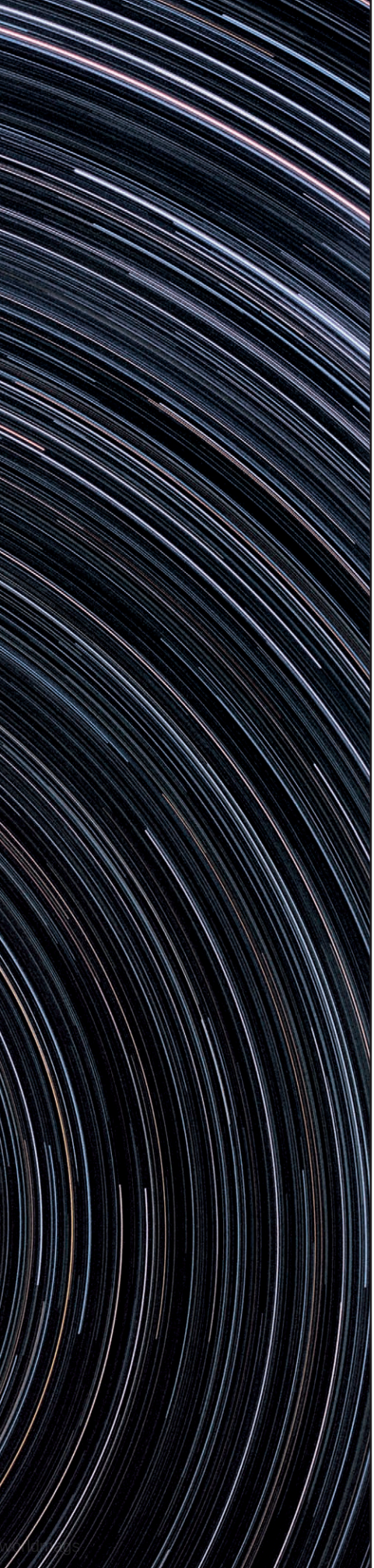
Left: The Greenpeace vessel *Esperanza* unloads one of the nine enclosures known as mesocosms (literally "midsize worlds") used in the acidification experiments. Developed by biological oceanographer Ulf Riebesell of the Leibniz Institute of Marine Sciences in Germany, the mesocosms consist of a buoyant frame and a 65-foot-long polyurethane bag that encloses plankton and other small marine organisms. Above: A device called a spider injects different concentrations of carbon dioxide into each mesocosm, altering its acidity. "We adjusted the CO_2 levels to simulate the ocean acidity expected in 20 years, 40, 60, and so on," Riebesell says. Top: Researchers at Spitsbergen collected more than 15,000 ocean water samples for analysis.

Spiked plastic roofs for the mesocosms prevent seabirds from landing on them. Norway's Svalbard archipelago hosts some 150 bird species, including the Arctic tern, which makes the longest migration of any animal (nearly 45,000 miles to the Antarctic and back). The tern feeds on plankton that may be affected by ocean acidification.

BOTTOM RIGHT: JEAN-PIERRE GATTUSO/LOV-CNRS-UPMC



Below: Three of the nine mesocosms –each containing some 15,000 gallons–float in Spitsbergen's Kongs Fjord. By testing how organisms fare at different acidity levels, researchers hope to understand whether there is a threshold pH that severely disrupts the ecosystem. Acidification has been linked to past mass extinctions, including the "Great Dying" of 250 million years ago, when 90 percent of marine species and 75 percent of those on land disappeared. Opposite: An empty mesocosm bag is collected after six weeks of sampling. Left: Shelled plankton called pteropods, like the one seen here through a microscope, are an important food source for fish, whales, and birds. Juvenile pteropods do not grow shells in lab studies simulating acidifying oceans. In the wild, this failure could leave them vulnerable to predators before they are able to mature and reproduce.



PHYSICS OF THE DIVINE

A group of scientists are embarking on a controversial search for God within the fractured logic of quantum physics.

By ZEEYA MERALI

WHEN HE DESCRIBES HIS LINE OF WORK, JOHN POLKINGHORNE JESTS, HE encounters "more suspicion than a vegetarian butcher." For the particle physicist turned Anglican priest, dissonance comes with the territory. Science parses the concrete: the structure of the atom and the workings of the brain. Religion confronts the intangible: questions about ethics and the purpose of life. Taken literally, the biblical story of Genesis contradicts modern cosmology and evolutionary biology in full.

Yet 21 years ago, in a move that made many eyes roll, Polkinghorne began working to unite the two sides by seeking a mechanism that would explain how God might act in the physical world. Now that work has met its day of reckoning. At a series of meetings at Oxford University last July and September, timed to celebrate Polkinghorne's 80th birthday, physicists and theologians presented their answers to the questions he has so relentlessly pursued. Do any physical theories allow room for God to influence human actions and events? And, more controversially, is there any concrete evidence of God's hand at work in the physical world?

Sitting with Polkinghorne on the grounds of St. Anne's College, Oxford, it is difficult to regard the jovial gentleman with suspicion. Oxford has been dubbed the "city of dreaming spires," and Polkinghorne is as

quintessentially English as the university's famed architecture, with college towers and church spires standing side by side. The bespectacled elder statesman of British science walks with a stick and wears hearing aids in both ears. But he retains a spring in his step and a quick wit. ("He will charm you in conversation, as long as you get him in his better ear," a colleague says.)

Polkinghorne's dual identity emerged early. He grew up in a devout Christian family but was always drawn to science, and in graduate school he became a particle physicist because, he explains modestly, he was also "quite good at mathematics." His scientific pedigree is none too shabby. He worked with Nobel laureate Abdus Salam while earning a doctorate in theoretical physics from Cambridge University, where he later held a professorial chair. One of his students, Brian Josephson, went on to win a share of the Nobel Prize in Physics in 1973. Polkinghorne himself joined Nobel laureate Murray Gell-Mann in research that led to the discovery of the quark, the building block of atoms. But in 1979, after 25 years in the trenches, Polkinghorne decided that his best days in physics were behind him. "I felt I had done my bit for the subject, and I'd go do something else," he says. That is when he left his academic position to be ordained.

Even as Polkinghorne changed careers, science seemed be making God's role in the world increasingly irrelevant. In 1988 his Cambridge colleague Stephen Hawking addressed the issue head-on in his wildly successful book, *A Brief History of Time,* concluding that the universe could have been created without any need to invoke a Creator. A year later Polkinghorne countered with *Science and Providence: God's Interaction With the World,* in which he framed the concept of divine action in a way that could be tackled by physicists. "I started with the statement that I believe that God acts in the world, but he is not a show-off conjurer who violates the same laws of nature that he made," he says. "My question was, Is there a way of describing God's actions that is consistent with science?"

As a priest with a past, Polkinghorne discussed the question with old friends. "Gell-Mann thought I was crazy," he says with a chuckle. But Salam, a practicing Muslim and one of the physicists to mathematically unify two of the fundamental forces of nature—electromagnetism and the weak force, which governs radioactivity—identified with Polkinghorne's quest. Even the most strident atheists from the old crowd enjoyed the debate. Steven Weinberg, who shared the Nobel with Salam in 1979, is a regular sparring partner. "Whenever we meet," Polkinghorne says, "he's always the one to put religious matters on the agenda, and though we don't agree, we always discuss things."

This spirit of respect persuaded another physicist and theologian, Bob Russell, to support Polkinghorne in his search for a physics of the divine. Russell, who founded the Center for Theology and Natural Sciences to foster interaction between science and religion in California in 1981 (before Polkinghorne was ordained), eventually teamed with the Vatican Observatory to launch a Divine Action Program. That group has been meeting with Polkinghorne and others to discuss religion and science ever since. "It's often assumed that scientists are intrinsically atheist," Russell says, "but science can be a spiritual experience. For some, it is about reading the mind of God."

IF DIVINE ACTION IS HIDDEN BY DESIGN, CAN

Reviewing the evidence at Polkinghorne's birthday conference at Oxford last July, Russell concluded that the best place to seek scientific support for God is in quantum mechanics, the physical laws describing the subatomic realm. Soon after quantum theory was developed in the early part of the 20th century, physicists realized it had some peculiar properties. For people seeking a place for God in the physical world, the most important of those properties is the uncertainty principle, which states that you can never predict the outcome of a quantum experiment with certainty; you can only calculate the probability of getting a particular result.

As a result of the uncertainty principle, quantum events are starkly different from those in the familiar, large-scale world. When you toss a coin, you could in theory make a foolproof prediction (heads or tails) if you knew every piece of information about the flip—the speed and height of the toss, the movement of all the air currents in the room, and so on. At the quantum scale, in contrast, equivalent events are intrinsically indeterministic: The universe simply does not contain enough information for you to predict a result. This fundamental indeterminism has been repeatedly confirmed in the lab. For instance, physicists have shown that two identical radioactive atoms will decay at different times. There is no way to explain why they behave differently or to predict the precise time of decay.

Russell notes that the known laws of physics do not force a quantum experiment to yield a certain result but allow a choice of outcomes. Perhaps God makes that choice, he argues, swooping in to manipulate the outcome and influence an event in the physical world. That interpretation not only allows a place for God but addresses a philosophical mystery that long bothered Einstein and many of his followers: Is there some deeper determinism that controls the outcome of seemingly random quantum events?

A major criticism of Russell's view of uncertainty as God's tool for shaping the world is that quantum events usually play out only on the subatomic level. There is no clear evidence that messing with the decay of atoms or the bouncing of electrons can affect human behavior or change the course of history. For instance, a midsize asteroid contains about 10^{40} atoms. An unthinkably large number of quantum events would need to be fixed to steer all of those atoms toward Earth in a way that would have led, say, to the extinction of the dinosaurs.

Polkinghorne pondered this problem for decades before finding a work-around in the byways of chaos theory, a branch of mathematics that describes the underlying order in large, seemingly unpredictable systems, from weather to economics. Through the machinery of chaos, a tiny change in

PREVIOUS PAGES: DAVID STEPHENSON, COURTESY JULIE SAUL GALLERY, NY

starting conditions can lead to vastly different outcomes over time. One common metaphor for how this might work is the so-called butterfly effect, the idea that a butterfly flapping its wings in Los Angeles could trigger a series of events that ends with a hurricane in China. Polkinghorne sees room for God in the deep mysteries of chaos theory and the limits of prediction. A divine intelligence in command of chaos could manipulate a vast number of quantum events with just a few well-chosen controls. The results could then grow large enough to have a meaningful impact on human lives.

Among other researchers, though, adding chaos to the argument did not help. Paul Ewart, an atomic and optical physicist at Oxford, describes himself as "pessimistic" about finding God hidden within the uncertainty principle, with or without chaos to lend a helping hand. From a scientist's perspective, the difficulty is that this model of divine action is by definition hidden from view, making an experiment to detect it almost impossible to devise. It would be like proving the reality of an invisible, tasteless, odorless, silent, intangible tiger lurking in your garden. Short of God's materializing in the lab and shouting, "Look at me!" Ewart notes, it is difficult to think of any incontrovertible proof. "I think we are an infinite distance from understanding God's workings," he says.

Quantum physicist Antoine Suarez of the Center for Quantum Philosophy in Zurich argues that the God seekers are better off pursuing another quantum effect, entanglement. In entanglement, two particles become twinned in such a way that the measurement of one always determines the properties of the other, no matter how far apart they may be. Imagine setting up a pair of entangled quantum "coins" (such as photons with a specific orientation), then giving one to Alice in Oxford and another to Bob in Zurich. When you ask Alice and Bob to flip their coins, they would both get heads or both get tails, even though the results of the tosses should be random and independent. Most physicists accept entanglement as just one more counterintuitive reality of quantum physics. But Suarez claims entanglement tests conducted with real photons in the lab suggest that quantum effects must be caused by "influences that originate from outside of space-time."

In an oft-repeated version of the photon experiment, a pair of entangled photons, A and B, are created by a laser beam. Each photon follows a different path around a table until it hits a "beam splitter," a half-silvered mirror that acts as a crossroads. From this point each photon continues its journey down one of two paths, either short or long—another type of quantum coin toss. In every case A and B will follow the same route, both traveling the long path or both traveling the short one. But why?

Seeking an explanation, Suarez and his colleague Valerio Scarani (now at the National University of Singapore) proposed a way to modify the basic experiment, which had been carried out by physicists in Geneva. Their intent was not to address theological questions but to challenge quantum theory by testing one of its fundamental predictions: that the timing of quantum events has nothing to do with their outcomes. They proposed instead that the outcome might be influenced by the course of events as the experiment takes place. For instance, if particle A hits the beam splitter even a tiny fraction of a second before particle B, its trajectory and outcome might influence what happens to B in its wake, somehow communicating across time. To test the idea, Suarez and Scarani needed to design an experiment that disrupted the cause-and-effect relationship between the photons by making sure that neither one arrived before the other.

A CUNNING EXPERIMENT BRING IT INTO VIEW?

THEIR CUNNING SCHEME was based on another famous theory of physics that gives quantum mechanics a run for its money in terms of odd predictions: Einstein's theory of relativity. Early in the 20th century, Einstein realized that time is not absolute; it runs at a slower or faster rate depending on how quickly you are moving. (Your watch falls about 177 nanoseconds behind on a cross-country flight.) Because relativity monkeys around with the rate at which time flows, there is no universal clock ticking away at a set rate that everyone will agree on. Two people moving relative to each other can even disagree on the order in which two events take place. If Alice and Bob are seated on two space shuttles moving in different directions, it is possible to set up a scenario in which they both flip quantum coins, but Alice says she flipped her coin before Bob, while Bob swears he tossed his coin first. According to Einstein, they would both be right, depending on whether you looked at the situation from Alice's or Bob's point of view.

In an analogous "before-before" experiment, Suarez's colleagues in Geneva deployed entangled photons A and B through beam splitters, after which each particle would follow either a short or a long path. The physicists used acoustic waves that had the effect of altering time for the photons—the equivalent of putting Alice and Bob in those opposite-moving space shuttles. In this setup, a miniature observer running alongside photon A would swear it had been set on its course first, while an observer next to photon B would say with equal certainty that events had happened in the reverse order.

Suarez was sure that by messing up the time-ordering in this way, it would be impossible for the photons to coordinate their paths. He was proved wrong. On every run, the photons still met the same fate. Whatever causes the twin photons to behave in the same way, it must work independently of time. "There is no story that can be told within the framework of space-time that can explain how these quantum correlations keep occurring," Suarez says.

These results have intriguing philosophical implications, he notes, especially for the spiritually inclined. "You could say the experiment shows that space-time does not contain all the intelligent entities acting in the world because something outside of time is coordinating the photons' results," Suarez says. "Physics experiments cannot

demonstrate the existence of God, but this test shows that today's physics is compatible with all major religious traditions. There is strong experimental evidence for accepting that nonmaterial beings act in the world."

Polkinghorne concurs. Although quantum physics itself is a purely material and mathematical description of the world, he says, "the mysteries of quantum objects leave room for God in an explanation of the physical world."

Other attendees at the Oxford events say that attributing quantum matchups to the hand of God is a leap of faith too far. Jean Staune, a mathematical physicist and philosopher at the Interdisciplinary University in Paris, who attended the September meeting, puts it like this: The before-before experiment shows that "if an intelligence is directing quantum events, then that intelligence exists outside the material universe. But it doesn't prove that such a mind exists."

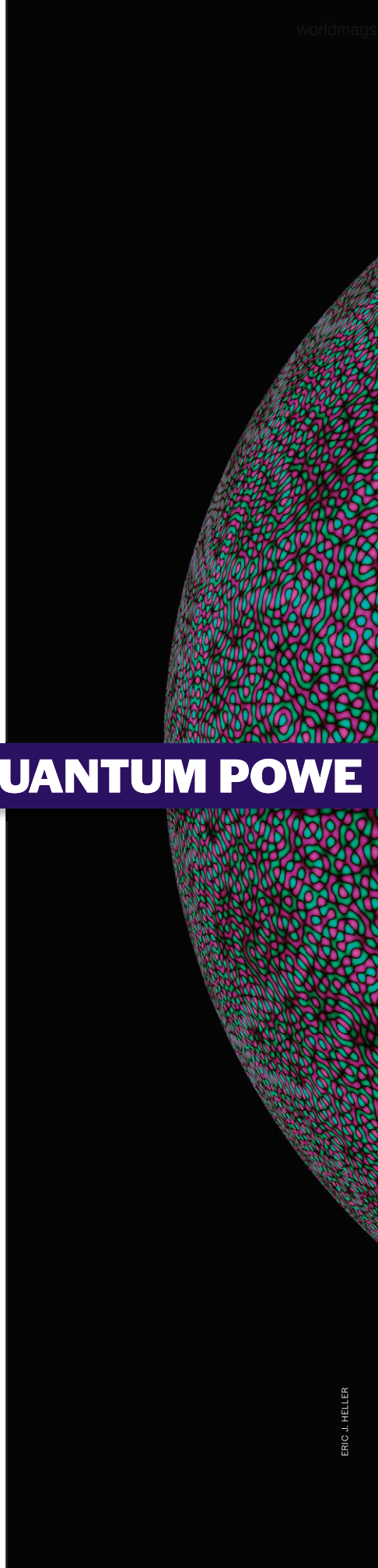
This gets to a pitfall Polkinghorne has worked hard to avoid: If you explain away every scientific unknown by invoking God, you end up with a "God of the gaps," one that can be eroded anew every time a new part of the science puzzle is solved. "The trouble is that if science later advances, God will be left high and dry," says Christopher Isham, a practicing Christian and a theoretical physicist at Imperial College London. He questions the merit of trying to validate religious experience by appealing to science. "For me, religious belief is more about mystical feelings about the world, and God is something one encounters in one's self," says Isham, who converted to Christianity at the age of 40. He was asked to act as an adviser on the Divine Action Program when it was conceived 20 years ago but has lost interest over time.

"Most physicists are amateur metaphysicists," adds Nicholas Saunders, a theologian who reviewed Polkinghorne's arguments for scientific evidence of divine action at the July meeting. Also a lawyer with some training in physics, Saunders admits he is "not a fan" of such theories—not so much because they yield bad science as because they lead to bad theology. For example, suppose you accept that God steps in every so often to fix the outcome of a quantum event in the brain—manipulating the motion of electrons to cause a neuron to fire, perhaps, influencing your decision on whether to become a priest or a scientist. In what sense would your career choice then really be your own? And if scientists ever did manage to uncover mechanisms used by God to influence the physical world, it would become even harder to defend why God does not use this power to alleviate suffering. "It does rather raise the question of why the universe is, frankly, a bit crummy," Saunders says. Discovering God's quantum powers would also seem potentially to give us godlike control ourselves, although Saunders is not too concerned: "It's one thing to understand a mechanism and another to manipulate it."

When I put these dissents to Polkinghorne, his jolly demeanor fades. "We need to find a middle ground where God is not a cosmic tyrant, with us as puppets," he concedes. "The answer has to lie along the lines that God has given humans real freedom, even if they grievously misuse it. But after seeing some of the horrific events that took place in the 20th century, it is hard to say that without a quiver in your voice."

Despite the many critiques that his work has inspired, Polkinghorne insists, in the wake of his birthday meetings, that the challenge to prove God compatible with physics has largely been met. "Physics asks how the world works, and when it answers that question it finds a very deep, marvelously patterned order. But it doesn't explain where that order comes from. I believe that the order is a reflection of the mind of God."

What about Isham's God-of-the-gaps concern, in which science explains it all, making God irrelevant for good? Polkinghorne counters that, by its very nature, science can never provide a complete picture of the world. "Without the concept of God," he says, "we'll always be forced to treat some things like strange, brute facts."



ERIC J. HELLER

Opposite: Waves on a sphere follow the unpredictable rules of quantum mechanics. Pages 48–49: The predictable trails of stars as Earth rotates.

RS GIVE US GODLIKE CONTROL OURSELVES?

WikiLeaks, cloud computing, surgery over the Internet: Four network experts discuss the future of life online.

NICK FEAMSTER, network security, Georgia Tech

WILLIAM LEHR, wireless technology, MIT

WEAVING A

PHOTOGRAPH BY

NEW WEB

ANDREW KORNYLAK

In 1969 scientists at the University of California, Los Angeles, transmitted a couple of bits of data between two computers, and thus the Internet was born. Today about 2 billion people access the Web regularly, zipping untold exabytes of data (that's 10^{18} pieces of information) through copper and fiber lines around the world. In the United States alone, an estimated 70 percent of the population owns a networked computer. That number grows to 80 percent if you count smartphones, and more and more people jump online every day. But just how big can the information superhighway get before it starts to buckle? How much growth can the routers and pipes handle? The challenges seem daunting. The current Internet Protocol (IP) system that connects global networks has nearly exhausted its supply of 4.3 billion unique addresses. Video is projected to account for more than 90 percent of all Internet traffic by 2014, a sudden new demand that will require a major increase in bandwidth. Malicious software increasingly threatens national security. And consumers may face confusing new options as Internet service providers consider plans to create a "fast lane" that would prioritize some Web sites and traffic types while others are routed more slowly.

Fortunately, thousands of elite network researchers spend their days thinking about these thorny issues. Last September DISCOVER and the National Science Foundation convened four of them for a lively discussion, hosted by the Georgia Institute of Technology in Atlanta, on the next stage of Internet evolution and how it will transform our lives. DISCOVER editor in chief Corey S. Powell joined Cisco's Paul Connolly, who works with Internet service providers (ISPs); Georgia Tech computer scientist Nick Feamster, who specializes in network security; William Lehr of MIT, who studies wireless technology, Internet architecture, and the economic and policy implications of online access; and Georgia Tech's Ellen Zegura, an expert on mobile networking.

The Conversation in Context: 12 Ideas That Will Reshape the Way We Live and Work Online

1. CHANGE HOW THE DATA FLOW

A good place to start is with the overburdened addressing system, known as IPv4. Every device connected to the Internet, including computers, smartphones, and servers, has a unique identifier, or Internet protocol (IP) address. "Whenever you type in the name of a Web site, the computer essentially looks at a phone book of IP addresses," explains Craig Labovitz, chief scientist at Arbor Networks, a software and Internet company. "It needs a number to call to connect you." Trouble is, IPv4 is running out of identifiers. In fact, the expanding Web is expected to outgrow IPv4's 4.3 billion addresses within a couple of years. Anticipating this shortage, researchers began developing a new IP addressing system,

POWELL: Few people anticipated Google's swift rise, the vast influence of social media, or the Web's impact on the music, television, and publishing industries. How do we even begin to map out what will come next?

LEHR: One thing the Internet has taught us thus far is that we can't predict it. That's wonderful because it allows for the possibility of constantly reinventing it.

ZEGURA: Our response to not being able to predict the Internet is to try to make it as flexible as possible. We don't know for sure what will happen, so if we can create a platform that can accommodate many possible futures, we can position ourselves for whatever may come. The current Internet has held up quite well, but it is **ready for some changes**[1] to prepare it to serve us for the next 30, 40, or 100 years. By building the ability to innovate into the network, we don't have to know exactly what's coming down the line. That said, Nick and others have been working on a test bed called **GENI**[2], the Global Environment for Network Innovations project that will allow us to experiment with alternative futures.

POWELL: Almost like using focus groups to redesign the Internet?

ZEGURA: That's not a bad analogy, although some of the testing might be more long-term than a traditional focus group.

POWELL: What are some major online trends, and what do they suggest about where we are headed?

FEAMSTER: We know that paths are getting shorter: From point A to point B, your traffic is going through fewer and fewer Internet service providers. And **more and more data are moving into the cloud**[3]. Between now and 2020, the number of people on the Internet is expected to double. For those who will come online in the next 10 years or so, we don't know how they're going to access the Internet, how they're going to use it, or what kinds of applications they might use. One trend is the proliferation of mobile devices: There could be more than a billion cell phones in India alone by 2015.

POWELL: So there's a whole universe of wireless connectivity that could potentially become an Internet universe?

FEAMSTER: Absolutely. We know things are going to look vastly different from people sitting at desktops or laptops and browsing the Web. Also, a lot of Internet innovation has come not from research but from the private sector, both large companies and start-ups. As networking researchers, we should be thinking about how best to design the network substrate to allow it to evolve, because all we know for sure is that it's going to keep changing.

"Our stake in the ground is that global **Internet traffic will quadruple by 2014,** and we believe 90 percent of consumer traffic will be **video-based.**"

–PAUL CONNOLLY, CISCO

POWELL: What kind of changes and challenges do you anticipate?

LEHR: We're going to see many different kinds of networks. As the Internet pushes into the developing world, the emphasis will probably be on mobile networks. For now, the Internet community is still very U.S.-centric. Here, we have very strong **First Amendment rights** (see "The Five Worst Countries for Surfing the Web," page 59), but that's not always the case elsewhere in the world, so that's something that could cause friction as access expands.

POWELL: Nearly 200 million Americans have a broadband connection at home. The National Broadband Plan proposes that everyone here should have affordable broadband access by 2020. Is private industry prepared for this tremendous spike in traffic?

CONNOLLY: Our stake in the ground is that global traffic will quadruple by 2014, and we believe 90 percent of consumer traffic will be video-based. The question is whether we can deal with all those bits at a **cost**[4] that allows stakeholders to stay in business. The existing Internet is not really designed to handle high volumes of media. When we look at the growth rate of bandwidth, it has followed a consistent path, but you have to focus on technology at a cost. If we can't hit a price target, it doesn't go mainstream. When we hit the right price, all of a sudden people say, "I want to do that," and away we go.

POWELL: As networks connect to crucial systems–such as medical equipment, our homes, and the electrical grid–disruptions will become costly and even dangerous. How do we keep everything working reliably?

LEHR: We already use the cyber world to control the real world in our car engines and braking systems, but when we start using the Internet, distributed networks, and resources on some cloud to make decisions for us, that raises a lot of questions. One could imagine **all kinds of scenarios**[5]. I might have an insulin pump that's controlled over the Internet, and some guy halfway around the world can hack into it and change my drug dosage.

FEAMSTER: The late Mark Weiser, chief technologist at the Xerox Palo Alto Research Center, said the most profound technologies are the ones that disappear. When we drive a car, we're not even aware that there's a huge network under the hood. We don't have to know how it works to drive that car. But if we start networking appliances or medical devices and we want those networks to disappear in the same way, we need to rely on someone else to manage them for us, so privacy is a huge concern. How do I give someone visibility and access so they can fix a problem without letting them see my personal files, or use my printer, or open my garage door? The issues that span usability and privacy are going to become increasingly important.

ZEGURA: I would not be willing to have **surgery over the Internet today**[6] because it's not secure or reliable enough. Many environments are even more challenging: disaster situations, remote areas, military

known as IPv6, more than a decade ago. IPv6 is ready to roll, and the U.S. government and some big Internet companies, such as Google, have pledged to switch over by 2012. But not everyone is eager to follow. For one, the jump necessitates costly upgrades to hardware and software. Perhaps a bigger disincentive is the incompatibility of the two addressing systems, which means companies must support both versions throughout the transition to ensure that everyone will be able to access content. In the meantime, IPv4 addresses, which are typically free, may be bought and sold. For the average consumer, Labovitz says, that could translate to pricier Internet access.

2. PUT THE NEXT INTERNET TO THE TEST

In one GENI experiment, Stanford University researcher Kok-Kiong Yap is researching a futuristic Web that seamlessly transitions between various cellular and WiFi networks, allowing smartphones to look for an alternative connection whenever the current one gets overwhelmed. That's music to the ears of everyone toting an iPhone.

3. MOVE DATA INTO THE CLOUD

As Nick Feamster says, the cloud is an increasingly popular place to store data. So much so, in fact, that technology research company Gartner predicts the estimated value of the cloud market, including all software, advertising, and business transactions, will exceed $150 billion by 2013. Why the boom? Convenience. At its simplest, cloud computing is like a giant, low-cost, low-maintenance storage locker. Centralized servers, provided by large Internet companies like Microsoft, Google, and Amazon, plus scores of smaller ones worldwide, let people access data and applications over the Internet instead of storing them on personal hard drives. This reduces costs for software licensing and hardware.

4. SETTLE WHO OWNS THE INTERNET

While much of the data that zips around the Internet is free, the routers and pipes that enable this magical transmission are not. The question of who should pay for rising infrastructure costs, among other expenses, is at the heart of the long-standing net neutrality debate. On the one side, Internet service providers argue that charging Web sites more for bandwidth-hogging data such as video will allow them to expand capacity and deliver data faster and more reliably. Opponents counter that such a tiered or "pay as

you go" Internet would unfairly favor wealthier content providers, allowing the richest players to indirectly censor their cash-strapped competition. So which side has the legal edge? Last December the Federal Communications Commission approved a compromise plan that would allow ISPs to prioritize traffic for a fee, but the FCC promises to police anticompetitive practices, such as an ISP's mistreating, say, Netflix, if it wants to promote its own instant-streaming service. The extent of the FCC's authority remains unclear, however, and the ruling could be challenged as early as this month.

5. UNDERSTAND WHAT CAN HAPPEN WHEN NETWORKS MAKE DECISIONS FOR US

In November Iranian president Mahmoud Ahmadinejad confirmed that the Stuxnet computer worm had sabotaged national centrifuges used to enrich nuclear fuel. Experts have determined that the malicious code hunts for electrical components operating at particular frequencies and hijacks them, potentially causing them to spin centrifuges at wildly fluctuating rates. Labovitz of Arbor Networks says, "Stuxnet showed how skilled hackers can militarize technology."

6. GET READY FOR VIRTUAL SURGERY

Surgeon Jacques Marescaux performed the first trans-Atlantic operation in 2001 when he sat in an office in New York and delicately removed the gall bladder of a woman in Strasbourg, France. Whenever he moved his hands, a robot more than 4,000 miles away received signals via a broadband Internet connection and, within 15-hundredths of a second, perfectly mimicked his movements. Since then more than 30 other patients have undergone surgery over the Internet. "The surgeon obviously needs a guarantee that the connection won't be interrupted," says surgeon Richard Satava of the University of Washington. "And you need a consistent time delay. You don't want to see a robot continually change its response time to your hand motions."

7. BRING ON THE MESSAGE FERRIES

A message ferry is a mobile device or Internet node that could relay data in war zones, disaster sites, and other places lacking communications infrastructure.

8. DON'T SHARE HARDWARE WITH PEOPLE WHOM YOU MIGHT NOT TRUST

Or who might not trust you. The tenuous nature of free speech on the Internet cropped up in settings. But many techniques have been developed to deal with places that lack robust communications infrastructure. For instance, my collaborators and I have been developing something called **message ferries**[7]. These are mobile routers, nodes in the environment that enable communication. Message ferries could be on a bus, in a backpack, or on an airplane. Like a ferry picks up passengers, they pick up messages and deliver them to another region.

POWELL: Any takers for surgery over the Internet? Show of hands?

LEHR: If I'm in the Congo and I need surgery immediately, and that's the only way they can give it to me, sure. Is it ready for prime time? Absolutely not.

POWELL: Many Web sites now offer services based on "cloud computing." What is the concept behind that?

FEAMSTER: One of the central tenets of cloud computing is virtualization. What that means is that instead of having hardware that's yours alone, you share it with other people, whom **you might not trust**[8]. This is evident in Gmail and Google Docs. Your personal documents are sitting on the same machine with somebody else's. In this kind of situation, it's critical to be able to track where data go. Several of my students are **working on this issue**[9].

POWELL: With more and more documents moving to the cloud, aren't there some complications from never knowing exactly where your data are or what you're connecting to?

LEHR: A disconnect between data and physical location puts providers in a difficult position—for example, Google deciding what to do with respect to filtering search results in China. It's a global technology provider. It can potentially influence China's rules, but how much should it try to do that? People are reexamining this issue at every level.

POWELL: In one recent survey, 65 percent of adults in 14 countries reported that they had been the victim of some type of cyber crime. What do people need to know to protect themselves?

FEAMSTER: How much do you rely on educating users versus shielding them from having to make sensitive decisions? In some instances you can prevent people from making mistakes or doing malicious things. Last year, for instance, Goldman Sachs was involved in a legal case in which the firm needed to show that no information had been exchanged between its trading and accounting departments. That's the kind of thing that the network should just take care of automatically, so it can't happen no matter what users do.

ZEGURA: I agree that in cases where it's clear that there is something people should not do, and we can make it impossible to do it, that's a good thing. But we can't solve everything that way. There is an opportunity to help people understand more about

> "The **most profound technologies are the ones that disappear.** When we drive a car, we're not even aware that there's a huge network under the hood."
>
> –NICK FEAMSTER, GEORGIA TECH

"I might have **an insulin pump** that's controlled over the Internet, and **some guy halfway around the world can hack** into it and change my drug dosage."

–WILLIAM LEHR, MIT

what's going on with networks so they can look out for themselves. A number of people don't understand how you can get e-mail that looks like it came from your mother, even though it didn't. The analogy is that someone can take an envelope and write your name on it, write your mother's name on the return address, and stick it in your mailbox. Now you have a letter in your mailbox that looks like it came from your mother, but it didn't. The same thing can happen with e-mail. It's possible to write any address on an Internet packet so it looks like it came from somewhere else. That's a very basic understanding that could help people be much smarter about how they use networks.

AUDIENCE: How is the Internet changing the way we learn?

FEAMSTER: Google CEO Eric Schmidt once gave an interview in which he was talking about how kids are being quizzed on things like county capitals. He essentially said, "This is ridiculous. I can just go to Google and search for capitals. What we really should be teaching students is where to find answers." That's perhaps the viewpoint of someone who is trying to catalog all the world's informa-

December when Amazon Web Services booted WikiLeaks from its cloud servers. Amazon charged that the nonprofit violated its terms of service, although the U.S. government may have had more to do with the decision than Amazon admits. WikiLeaks, for its part, shot back on Twitter, "If Amazon are [sic] so uncomfortable with the First Amendment, they should get out of the business of selling books."

Unfortunately for WikiLeaks, Amazon is not a government agency, so there is no First Amendment case against it, according to Internet scholar and lawyer Wendy Seltzer of Princeton University. You may be doing something perfectly legal on Amazon's cloud, Seltzer explains, and Amazon could give you the boot because of government pressure, protests, or even too many service calls. "Service providers give end users very little recourse, if any," she observes. That's why people are starting to think about "distributed hosting," in which no one company has total power, and thus no one company controls freedom of speech.

9. MAKE CLOUD COMPUTING SECURE

Nick Feamster's strategy is to tag sensitive information with irrevocable digital labels. For example, an employee who wants only his boss to read a message could create a label designating it as secret. That label would remain with the mes-

The Five Worst Countries for Surfing the Web

CHINA

Government control of the Internet makes using the Web in China particularly limiting and sometimes dangerous. Chinese officials, for instance, imprisoned human rights activist Liu Xiaobo in 2009 for posting his views on the Internet and then blocked news Web sites that covered the Nobel Peace Prize ceremony honoring him last December. Want to experience China's censorship firsthand? Go to baidu.com, the country's most popular search engine, and type in "Tiananmen Square massacre."

NORTH KOREA

It's hard to surf the Web when there is no Web to surf. Very few North Koreans have access to the Internet; in fact, due to the country's isolation and censorship, many of its citizens do not even know it exists.

BURMA

Burma is the worst country in which to be a blogger, according to a 2009 report by the Committee to Protect Journalists. Blogger Maung Thura, popularly known in the country as Zarganar, was sentenced to 35 years in prison for posting content critical of the government's aid efforts after a hurricane.

IRAN

The Iranian government employs an extensive Web site filtering system, according to the press freedom group Reporters Without Borders, and limits Internet connection speeds to curb the sharing of photos and videos. Following the controversial 2009 reelection of president Mahmoud Ahmadinejad, protesters flocked to Twitter to voice their displeasure after the government blocked various news and social media Web sites.

CUBA

Only 14 percent of Cubans have access to the Internet, and the vast majority are limited to a government-controlled network made up of e-mail, an encyclopedia, government Web sites, and selected foreign sites supportive of the Cuban dictatorship. Last year Cuban officials accused the United States of encouraging subversion by allowing companies to offer Internet communication services there. ANDREW GRANT

sage as it passed through routers and servers to reach the recipient, preventing a snooping coworker from accessing it. "The file could be altered, chopped in two, whatever, and the label would remain with the data," Feamster says. The label would also prohibit the boss from relaying the message to someone else. Feamster expects to unveil a version of his labeling system, called Pedigree, later this year.

10. MANAGE YOUR JUNK MAIL

A lot of it. Spam accounts for about 85 percent of all e-mail. That's more than 50 billion junk messages a day, according to the online security company Symantec.

11. PRIVACY IS DEAD? DON'T BELIEVE IT

As we cope with the cruel fact that the Internet never forgets, researchers are looking toward self-destructing data as a possible solution. Vanish, a program created at the University of Washington, encodes data with cryptographic tags that degrade over time like vanishing ink. A similar program, aptly called TigerText, allows users to program text messages with a "destroy by" date that activates once the message is opened. Another promising option, of course, is simply to exercise good judgment.

12. NETWORK TO MAKE A BETTER WORLD

Crowdsourcing science projects that harness the power of the wired masses have tremendous potential to quickly solve problems that would otherwise take years to resolve. Notable among these projects is Foldit (fold.it), an engaging online puzzle created by Seth Cooper of the University of Washington and others that tasks gamers with figuring out the shapes of hundreds of proteins, which in turn can lead to new medicines. Another is the UC Berkeley Space Sciences Lab's Stardust@home project (stardustathome.ssl.berkeley.edu), which has recruited about 30,000 volunteers to scour, via the Internet, microscope images of interstellar dust particles collected from the tail of a comet that may hold clues to how the solar system formed. And Cornell University's NestWatch (nestwatch.org) educates people about bird breeding and encourages them to submit nest records to an online database. To date, the program has collected nearly 400,000 nest records on more than 500 bird species. Check out discovermagazine.com/web/citizenscience for more projects.

ANDREW GRANT AND ANDREW MOSEMAN

"What happens **when a company you thought you trusted** gets bought or goes out of business and **sells all of your data** to the lowest bidder?"

–NICK FEAMSTER, GEORGIA TECH

tion and says, "Why don't you use it?" But there's something to be said for it—there's a lot of data at our fingertips. Maybe education should shift to reflect that.

AUDIENCE: Do you think it will ever be possible to make the Internet totally secure?

FEAMSTER: We'll never have perfect security, but we can make it tougher. **Take the problem of spam**[10]. You construct new spam filters, and then the spammers figure out that you're looking for messages sent at a certain time or messages of a certain size, so they have to shuffle things up a bit. But the hope is that you've made it harder. It's like putting up a higher fence around your house. You won't stop problems completely, but you can make break-ins inconvenient or costly enough to mitigate them.

AUDIENCE: Should there be limits on how much personal information can be collected online?

ZEGURA: Most of my undergraduate students have a sensitivity to private information that's very different from mine. But even if we're savvy, we can still be unaware of the personal data that some companies collect. In general, it needs to be much easier for people to make informed choices.

FEAMSTER: The thing that scares me the most is what happens when a company you thought you trusted gets bought or goes out of business and sells all of your data to the lowest bidder. There are too few regulations in place to protect us, even if we understand the current privacy policies.

LEHR: Technologically, Bill Joy [cofounder of Sun Microsystems] was right when he said, "**Privacy is dead**[11]; just get over it." Privacy today can no longer be about whether someone knows something, because we can't regulate that effectively. What matters now is what they can do with what they know.

AUDIENCE: Wiring society creates the capacity to crash society. The banking system, utilities, and business administration are all vulnerable. How do we meaningfully weigh the benefits against the risks?

LEHR: How we decide to use networks is very important. For example, we might decide to have separate networks for certain systems. I cannot risk some kid turning on a generator in the Ukraine and blowing something up in Kentucky, so I might keep my electrical power grid network completely separate. This kind of question engages more than just technologists. A wider group of stakeholders needs to weigh in.

CONNOLLY: You always have to balance the good versus the potential for evil. Occasionally big blackouts in the Northeast cause havoc, but if we decided not to have electricity because of that risk, that would be a bad decision, and I don't think it's any worse in the case of the Internet. We have to be careful, but there's so much possibility for enormous good. **The power of collaboration**[12], with people working together through the Internet, gives us tremendous optimism for the kinds of issues we will be able to tackle.

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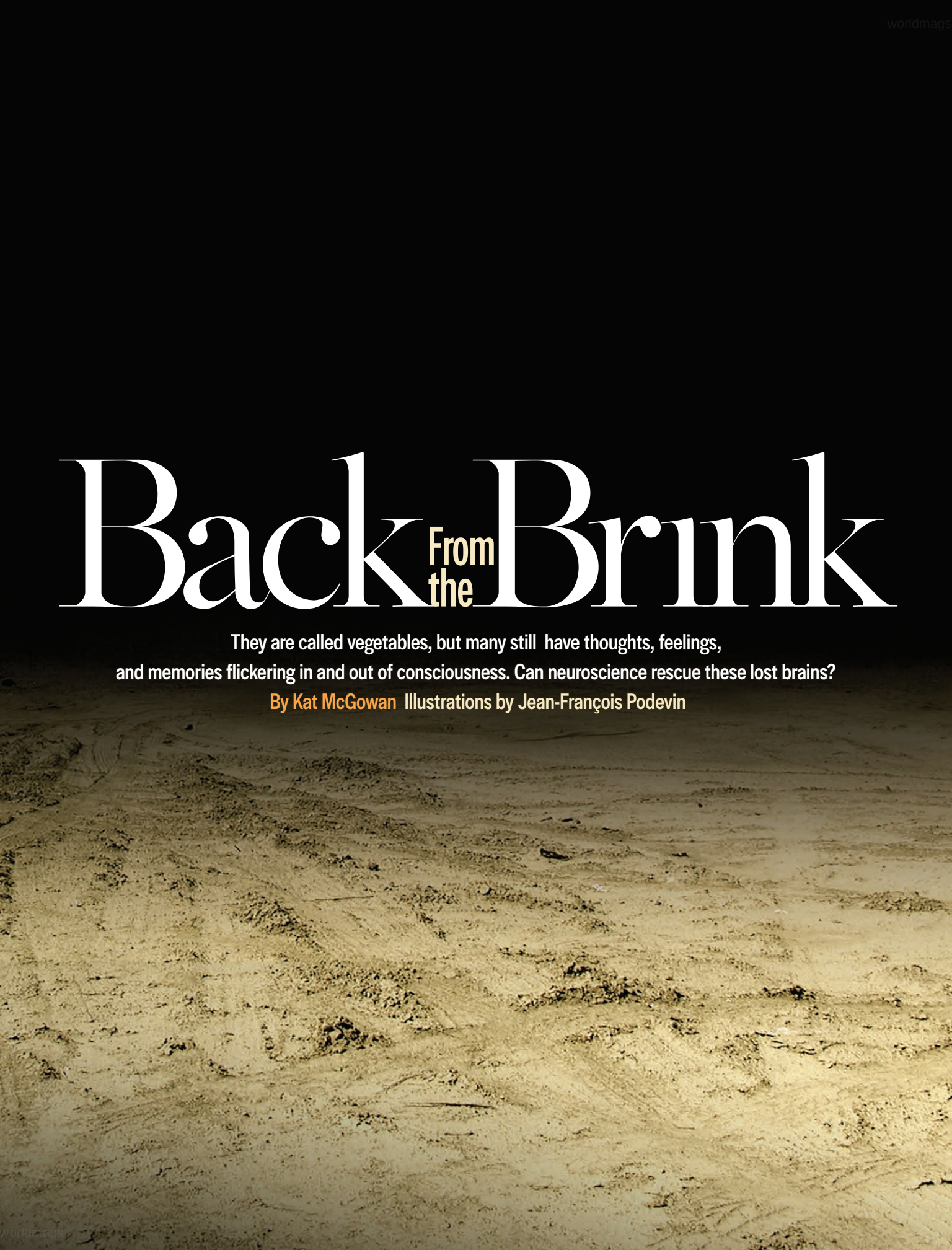
P13002

Back From the Brink

They are called vegetables, but many still have thoughts, feelings, and memories flickering in and out of consciousness. Can neuroscience rescue these lost brains?

By Kat McGowan Illustrations by Jean-François Podevin



THE WOMAN IN THE WHEELCHAIR WEARING BURGUNDY SCRUBS is lovely, with full eyebrows arching over her closed eyes. Joseph Giacino, director of rehabilitation neuropsychology at Spaulding Rehabilitation Hospital in Boston, squats beside her, looking into her face. "Hi, Kellie, it's Dr. Giacino. How are you? Can you open your eyes?"

No response.

Two and a half months ago, during what was supposed to be a simple nasal operation for sinusitis, Kellie's left carotid artery was accidentally sliced open, starving half her brain of blood and oxygen. Since that day, she has not spoken or clearly responded in any way. She opens her eyes, and sometimes she groans or gropes toward people nearby. Most of the time she seems to be asleep.

Is Kellie still in there? Giacino, 52, an expert in disorders of consciousness, will establish her condition more precisely with this exam. First, though, he needs Kellie to be more alert. He rubs her arm and her leg firmly, applying deep-muscle pressure, and her dark eyes pop open. She begins to breathe heavily and to shake. Giacino soothes her. "I'm just waking you up," he says gently. "You had some bleeding in your brain, and we're trying to help you get better." The expression on her face is intense and hard to read. It mixes fear with annoyance, as if she has just woken from a nightmare. "Every kid has a dad and a…" he prompts. She moans, or is she trying to say "mom"? It is difficult to tell whether she is oblivious or struggling to respond. When she makes eye contact and holds it, she seems just as aware as anyone else in the room. By her fierce expression, she looks as if she is about to tell Giacino to buzz off. Yet she does not speak. That is why this exam, calibrated to distinguish between reflexes and real cognition, is so important. When Giacino hands her a toy ball, she grabs it, smoothly and naturally. It is a good sign.

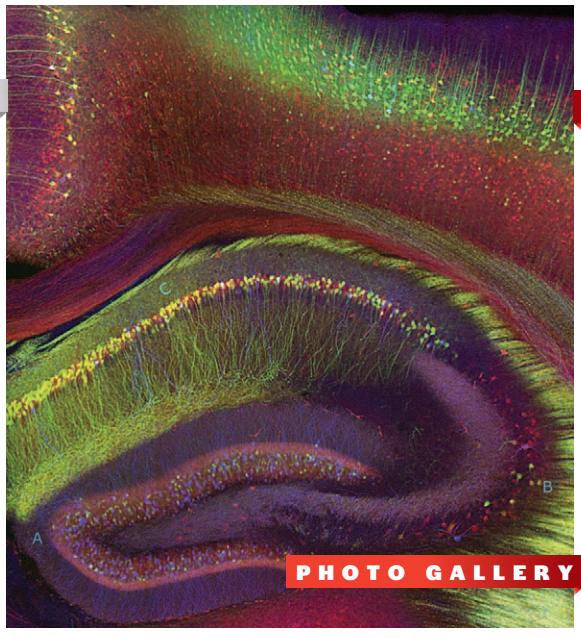
Just a few years ago, a patient like Kellie would have been written off. Anyone who did not regain consciousness within a few weeks after a stroke or head injury was said to have no hope for meaningful improvement. But in the past decade, a series of increasingly spectacular experiments conducted by Giacino and Weill Cornell Medical Center neurologist Nicholas Schiff has proved that this bleak verdict is often wrong. The semiconscious brain is not a useless sack of neural goo, they have shown, and not all damaged brains are the same. Disorders of consciousness come in shades of gray, from severely impaired "vegetative states" to the perplexing "minimally conscious state" in which people slip into and out of awareness. By studying patients who emerge into consciousness after years in limbo, Schiff and Giacino have shown that the brain can sometimes fix itself even decades after damage. They have discovered apparently vegetative people whose minds can still imagine, still recognize, still respond. In turn, these profoundly disabled people have opened the door to one of the last great mysteries of science: the nature of consciousness.

Schiff, Giacino, and the handful of other scientists doing this work worldwide hope to help more brain-injured people make the leap back into consciousness. In the meantime, the implications of their work are haunting. It suggests that many of the estimated 250,000 to 300,000 or more people in this country languishing in bedrooms and nursing homes with disorders of consciousness are probably still "in there"—still have some capacity to think and to feel and might, in a limited way, be able to rejoin the world. "These are human beings who seem to have lost their humanity," Giacino says. "The question is, is that really the case?"

The old verdict was harsh but clear-cut: Mourn your loved one, because he or she is gone. Now people like Kellie's husband, Mark, are tormented by hope and uncertainty. Giacino's exam establishes that Kellie is in the no-man's-land of the minimally

Dead People Who Can't R.I.P.

Some celebrities can't escape the limelight, even when they are long gone. Investigators still examine King Tut's remains and DNA to learn about ancient Egyptians and conduct postmortems to determine how historical superstars like Napoleon died.
discovermagazine.com/web/dead



Visualizing the Brain

Neuroscientists know the first step in understanding the brain is to get a good look at it, but producing detailed images is a maddeningly difficult task. This gallery explores a stunning new book, *Portraits of the Mind* (Abrams), showcasing researchers' finest attempts to map the brain throughout history, from 19th-century drawings to cutting-edge genetic techniques that produce colorful "brainbows."
discovermagazine.com/web/mind-portraits

Building a Telescope to Trump the Hubble

At sites around the country, NASA technicians are building the James Webb Space Telescope, which will be humanity's premier eye in the sky when it launches in 2014. Check out this sneak peek at its construction, including a view of the 21-foot-wide mirror that could reveal galaxies born just after the Big Bang.
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Not Exactly Rocket Science

Ed Yong delights in a tale of precocious scientists: 8-year-old students who designed experiments investigating bumblebees, carried out the research, and published their findings in the prestigious journal *Biology Letters.* (The paper's figures are in colored pencil.)
discovermagazine.com/web/kid-science

Bad Astronomy

After 33 years of travel, the Voyager 1 probe has now reached the edge of our solar system, where the solar wind slows to a stop. Says Phil Plait, "Literally, the wind is no longer at Voyager's back."
discovermagazine.com/web/voyager-1

Cosmic Variance

Sean Carroll examines a splashy new paper on cyclic cosmology, which claims to find evidence of universes that existed before the Big Bang. The skeptics are already weighing in.
discovermagazine.com/web/cyclic-cosmology

Gene Expression

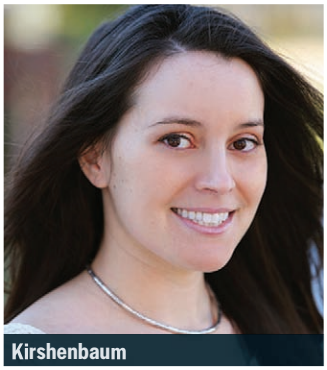
A new study maps the ancient waterways that crisscrossed the Sahara during the region's humid phases, and Razib Khan explains what this "green Sahara" may have meant for human migrations out of Africa.
discovermagazine.com/web/green-sahara

Science Not Fiction

Kyle Munkittrick asks a serious question: Are there any circumstances under which you'd feel OK about eating Soylent Green (which, as sci-fi movie fans know, is made out of people)?
discovermagazine.com/web/soylent

The Loom

For months a controversy has raged over Mono Lake microbes that researchers claimed were capable of using arsenic to build their DNA. Carl Zimmer, who has closely followed the debate, presents the opinions of the many scientists he interviewed on the subject.
discovermagazine.com/web/arsenic


Kirshenbaum

The Intersection

To mark the release of her new book, *The Science of Kissing: What Our Lips Are Telling Us,* Sheril Kirshenbaum is answering readers' questions about kissing and romantic compatibility, smooches in the animal kingdom, and more.
discovermagazine.com/web/kissing

FROM LEFT: ISTOCKPHOTO; TAMILY WEISSMAN/JEFF LICHTMAN/JOSHUA SANES; NASA/MSFC/EMMETT GIVENS

The first vegetative patient Schiff saw, the victim of a stroke, had no sign of consciousness. But when he ran into her three years later at a rehab center, he was shocked to find her awake and capable of talking to him.

conscious state. Whether she will return is anyone's guess. "The very hard part for me is looking into her deep brown eyes and not knowing what she is thinking," Mark wrote on his Web site in late August. "Is she mad at me? Is she in pain? Is this process torturing her? We don't know. These are the questions that keep me up, pretty much every night."

In the 1970s, when intensive care dramatically improved the survival of brain-injured patients, doctors found that if the body can be kept alive, the brain usually shakes off a coma—a totally unresponsive, eyes-closed state—within two to four weeks. At that point some people simply wake up, although they may be delirious and impaired. Others graduate to an in-between zone that New York Hospital–Cornell Medical Center neurologist Fred Plum labeled the "persistent vegetative state" in 1972. At the time, among these patients, it seemed as if only "vegetative" brain functions like breathing, waking, and blinking were working. The higher functions commonly associated with consciousness seemed to be lost.

The patients, doctors found, usually had widespread brain damage, but two injured areas were especially noteworthy: the thin outer rind, called the cortex, and the thalamus, a pair of walnut-size lumps in the brain's central core, along with the neural fibers that connect these regions. The two areas are normally in constant cross talk, filtering and analyzing sensory data and making continual adjustments to attention and alertness. Lacking this chatter, someone in a vegetative state seems to be awake but not aware. They might moan and shift around, but they do not look toward a loud hand clap or pull away from a pinch. Given a feeding tube and basic medical care, someone might stay in this condition from days to decades, potentially until death.

Until recently, few neurologists besides Plum were interested in learning more. The consensus was that semiconscious brains do not heal, especially not months or years after an injury, so research and aggressive treatment were futile. But the very first vegetative patient Schiff ever saw, during his first month as a resident at New York Hospital in 1993, told a different story.

This woman had had a stroke more than six months earlier. When Schiff examined her, he found no sign of consciousness, just as expected. Three years later, on a visit to a local rehabilitation center, he ran into his former patient again. Not only was she awake, but she spoke to him. "I was shocked," he says now. "I remember the visceral feeling of having seen somebody come back from the dead. It seemed truly surreal."

Around the same time, Schiff heard about a female patient who had been in a vegetative state for nearly 20 years but sometimes blurted out a word, usually obscene. His first thought was that she could not possibly be vegetative. He and Plum, who had become his mentor, arranged for her to be part of a study using positron emission tomography, better known as a PET scan. This technique uses radioactive markers to map the brain's sugar metabolism—and, by implication, the speed at which neurons are firing.

When Schiff and Plum got this patient's scans back, they were confused. The PET scan looked blank. Her injured brain was functioning at such a low level that the normal rich glow of activity was barely a glimmer. When the researchers recalibrated the display screen, though, they could see tiny blobs of neural action in brain regions specialized for speech. Consciousness requires connectivity, and her vegetative brain was mostly disconnected. Nevertheless, this one isolated loop remained hooked up and active. Amid her scorched neural landscape, it spat out an occasional word, without meaning or conscious will.

The following year, 1997, another patient brought Schiff to the JFK Johnson Rehabilitation Institute in Edison, New Jersey, where he met Giacino. They made a good team. Schiff was a neuroscientist, probing the nuts and bolts of the brain; Giacino was a diagnostic master, devising better ways to evaluate semiconscious patients. With the support of Joseph Fins, chief of the department of medical ethics at Weill Cornell, who articulated the ethical arguments for why these patients must be studied and treated, they used PET to look at four more people in vegetative states. Metabolically, all the brains were limping along, underactive and underaroused. Yet each patient's pattern was idiosyncratic, showing unique clusters of remnant neural activity. "People look at these patients and say, 'They're all the same; they don't respond; their brain doesn't work,'" Giacino says. "This was a beautiful illustration of how dramatic the differences are."

For their next act, the two researchers turned to another mystery, the much larger number of semiconscious brain-injured patients who are severely disabled but not truly

vegetative. (In the United States, these are estimated at 280,000 cases versus 35,000 patients in the vegetative state.) These people are not merely awake but also partly aware. In them, consciousness is neither on nor off; it is unstable, emerging and fading "like the smile on the Cheshire cat," Schiff says. On good days they might follow people or objects with their eyes, nod, laugh, even say a word. On bad days they do not react at all.

Schiff and Giacino, working with Columbia University neuroimaging expert Joy Hirsch and graduate student Diana Rodriguez-Moreno, started probing these unpredictable brains in 2001 using functional magnetic resonance imaging (fMRI), which tracks the minute changes in blood oxygenation that correspond to neural activity. They reasoned that some regulatory mechanism of the brain must be oscillating up and down, creating these wide swings in awareness, and fMRI might clarify what it was. In 2002 a group of neurologists led by Giacino formally chose the term "minimally conscious" to describe these patients.

One subject who fell into this category was a man who had been beaten and kicked in the head during a robbery several years back. About 30 percent of the time, he was able to follow instructions, indicating "yes" or "no" by looking at a card, but he only rarely spoke a word or two. Most of the time, he kept his eyes closed. While he was undergoing fMRI, the team played a recording of his mother's voice. They expected to see isolated flares of activity in simple language-processing regions. Instead, the whole network of cortical regions specialized for hearing and language comprehension fired up, just as in a healthy brain. "It was stunning," Giacino says. The patient's visual cortex was buzzing too, as if the sound of his mother's voice had conjured up her face. A second subject responded in much the same way.

In some types of brain injury, people eventually regain full consciousness, with normal awareness and intellect, but are trapped in an unresponsive body; they are said to be "locked in." But the two patients in this study clearly did not rise to that level. As part of the experiment, the team played recordings of speech that had been reversed. In healthy subjects, language-processing regions become more active when they hear such backward speech, working hard to interpret strange-sounding words. These patients' brains reached only the earliest stages of response, as if they could not engage enough to ask, "Hey, what's that?" The difference between a vegetative and a minimally conscious brain was looking like a question of how much brain wiring remained intact and, more important, still able to pass along a signal. Neurologist Steven Laureys of the University of Liège in Belgium, who would later collaborate with Schiff and Giacino, showed that same year, 2002, that in vegetative patients, mild electric shocks activated basic sense-perception regions but not the higher-level information processing networks that the minimally conscious patients could access.

The brain scans of the robbery victim had revealed enough connectivity and enough bandwidth to register and process a human voice. What the patient could not do was maintain his awareness. Since medical school, Schiff had believed that a technique called deep brain stimulation might help patients who have viable, net-

The night of his beating, his mother was told he would never be more than a vegetable, but with the stimulator switched on, he can swallow, hold a cup, name objects, speak short sentences, and smile.

worked cortical tissue but inconsistent awareness. In deep brain stimulation, electrodes are permanently installed in the brain, like a neural pacemaker. (It is most often used to help people with Parkinson's disease regain control over their limbs.) Such stimulation had not worked very well in a trial conducted on vegetative patients in the 1980s by the medical device company Medtronic. But Schiff, who had been mapping the pathways of consciousness, was convinced that Medtronic had picked the wrong patients—those who were catastrophically injured and beyond help—and had put the electrodes in the wrong place.

He had his eye on a distinctive part of the central thalamus, a circumscribed region within a group of neurons known as the intralaminar nuclei. In a normal brain, the neurons of the central thalamus crackle with electrical activity when we struggle to pay attention to the world around us, and they accelerate their action as we emerge from sleep. Anatomically, these neurons have widespread connections to the brain stem, a primitive region that controls waking and sleep; to nearby basal ganglia involved in movement; and to the medial frontal lobes, which are involved in motivation. Because of this architecture, the cells of the thalamus can buzz many regions at once to redirect attention, synchronize information processing, or kick-start activity. Long, thin fibers called axons extend from neural cells, and the particular geometry of the thalamus, with its many connections, makes it particularly vulnerable to injury. A shock wave from a blast or blow to the head, rippling through soft neural flesh, can sever the axons. The neurons then stop working or die, and the signal from the thalamus weakens, Schiff believes. The brain gets stuck in idle.

If deep brain stimulation could dial a patient's thalamus back up, Schiff expected that it would activate the rest of the brain as well. In February 2005, six years after his injury, the robbery victim was taken to the Cleveland Clinic, where a surgeon installed millimeter-thick platinum-iridium wires that could transmit electricity or receive neural signals. When fed through an amplifier, the signals from healthy neurons sound like Velcro being unhooked. But as the electrodes poked into this man's thalamus, Schiff and Giacino heard only silence, the eerie calm of a stalled-out brain.

As soon as the researchers switched the stimulator on, Giacino says, the man's eyes opened. The doctors were not yet sure that it worked; they waited two months for the patient to completely heal from surgery before beginning their cognitive tests. For Schiff, the real moment of drama came during one of those first sessions, when the patient had the electrodes fully switched on for several hours. Schiff and Giacino showed him a picture of a red Radio Flyer, and before Schiff even remembered what the toy was called, the patient said, "Wagon."

As months passed his repertoire increased; with the stimulator switched on, he could swallow, hold a cup, name objects, speak short sentences, and smile. The real impact of the stimulation is best described by his mother, who had been told the night of his beating that he would never be more than a vegetable. "My son can now eat, speak, and watch a movie without falling asleep," she said through tears at a press conference announcing the results of the study. "He can express pain. He can cry and he can laugh. The most important part is, he can say 'Mommy' and 'Pa.' He can say, 'I love you, Mommy.'"

What had it been like in limbo? The patient cannot say; like others who have emerged from disorders of consciousness, he does not remember anything about the experience. "Is it like waking up from surgery? Is it like being very groggy after you've been concussed? Who knows?" Schiff says. Maybe it is like waking up with jet lag in a dark hotel room far from home, speculates Caltech biologist Christof Koch, who also studies consciousness. At that moment, you have no idea where you are or how you got there. You simply know that you exist.

The impossibility of knowing gets to a core problem of consciousness: There is no way to measure it objectively. Normally we use people's behavior as a proxy for their internal state. But you cannot trust what your eyes and your ears tell you about someone with a disorder of consciousness.

In 2005, just as the deep brain stimulation patient was making his first forays into awareness, the fate of Terri Schiavo, a Florida woman who had been in a vegetative state since 1990, sparked an ideological war. Her husband wanted her feeding tube removed, believing that she would not have wanted to live that way; her parents disagreed. Eventually, everyone from the governor of Florida to the U.S. Congress took sides. The arguments hinged on different impressions of how much awareness Schiavo still retained. A clip of Schiavo smiling was shown over and over again on TV. Senate majority leader Bill Frist (a Harvard Medical School graduate) insisted that the video meant she was still conscious, a gut intuition that was as powerful as it was wrong. Eventually her feeding tube was removed and she died, and an autopsy proved that she

Have we been killing people? The answer is almost certainly yes. After a brain injury, doctors may paint a dim picture of the future, and families may withdraw care. But it is increasingly difficult to predict who will linger in limbo and who will make strides.

could never have recovered. Her brain had shriveled to less than half the weight it should have been.

More often, brain-injured patients are more conscious than they appear because physical problems limit their responses. Their muscles often become permanently clenched in contracture so they cannot move their arms and legs. They may be deaf or blind, unaware of a neurologist's questions. They may be in too much pain to pay attention. Just staying awake with an under-aroused brain is difficult, and many patients receive muscle-relaxing drugs that make them even sleepier.

And sometimes doctors just fail to catch a patient's subtle or rare fluctuations in awareness. These people are like a Rorschach test, Schiff says; where families see signs of cognition, doctors may see only wishful thinking. "There's a kind of complacency about it—'What you see is what you get,'" he adds. "Some people don't have the intellectual curiosity or imagination to anticipate some of the things you might find when you start looking." Three separate studies, the most recent in 2009, indicate that up to 43 percent of people diagnosed as being in a vegetative state are, when more carefully examined, found to be at least partly aware.

Underestimating consciousness can have tragic consequences. Vegetative patients probably do not feel pain, but imaging experiments indicate that minimally conscious patients do, even if they cannot always react to it. In a European survey, 66 percent of health-care professionals said they thought it was permissible to remove a feeding tube from someone who had been in a vegetative state for more than a year, but only 28 percent felt that way for patients who were minimally conscious. When Schiff gave a grand rounds talk to a group of medical students, residents, and doctors last spring, a young neurologist brought up the elephant in the room. "We're asked early on, when the patient is still in the intensive care unit, what the prognosis is for meaningful recovery for a patient who seems vegetative," he said. "The family often withdraws care when we say there's no chance. Have we been killing people?"

Schiff does not directly respond, but the answer is almost certainly yes. In the immediate aftermath of a massive brain injury, doctors tend to paint a grim picture of the future. Many feel that a good doctor is obligated to help a family let go of unrealistic hope. "One has to help people just face the facts," says William Landau, who for two decades was head of neurology at the school of medicine at Washington University in St. Louis. "Otherwise their hope goes on forever, and the tragedy and human cost go on forever, while the ability to live autonomously never comes."

The problem, Schiff, Fins, and Giacino say, is that it is increasingly hard to predict early on who will linger for years in limbo and who will make significant strides. People who regain consciousness a year or more after injury rarely return to normal; many remain bedridden, incontinent, confused, or agitated. But as lifesaving interventions grow steadily more sophisticated, the course of recovery from severe brain injury is often much better than it used to be. If a patient escapes outright brain death, some improvement can be expected, especially among those who survive trauma rather than oxygen-deprivation injuries, such as a stroke or heart attack. In a recent small study, 16 out of 18 minimally conscious trauma patients recovered consciousness within five years. Four still needed 24-hour care, but another five were working or studying part-time. "To paint a dire picture about somebody with an uncertain diagnosis, early in the course, is to misrepresent reality and misunderstand one's obligation as a doctor," Fins says. "It's wholly wrong and unethical to obscure those facts."

Some injuries are obviously catastrophic, but for many patients, it takes weeks or months to know who will wind up where. When Giacino examined Kellie in late summer, the diagnosis of "minimally conscious" seemed promising. In the fall, however, after struggling with infections and other complications, she stopped moving the left side of her body. She died in mid-December. Just as unpredictably, other patients get better. One research subject was a 58-year-old woman who was in a minimally conscious state after a stroke. Her age and her injury suggested a dire outcome, but three years later she was awake and talking.

Schiff, Fins, and Giacino still struggle to convince their colleagues that their findings are not flukes, that they are not attributing meaning to mere reflexes. "I went to a well-regarded major medical center to speak to the trauma team, and I did my whole spiel, an hour-long lecture with everybody there: residents, attending physicians, the head of trauma," Giacino says. "I explained how we go through the assessment process, the importance of differential

diagnosis, distinguishing between vegetative state and minimally conscious state. The head of trauma thanks me and in a very jovial manner says, 'In my day, the term for these patients was *jellyfish*.' And he laughs and moves on. What do you do with that?"

One way to convince the skeptics is with better biological evidence. Indications that a person can be cognizant and yet show absolutely no outward sign keep getting stronger. In 2006 a group led by neuroscientist Adrian Owen of the Medical Research Council in Cambridge, England, used neuroimaging to pick up the thoughts of a woman who had been in a vegetative state for five months after a traffic accident. He asked her to imagine one of two scenes—playing tennis or walking around her house—for 30-second intervals while having an fMRI. In a normal brain, imagining tennis activates the supplementary motor area of the cortex, and picturing one's home prompts activity in regions involved in spatial perception, such as the posterior parietal cortex. This patient's brain responded exactly the same way.

Some neurologists said these responses could be largely unconscious, so Owen, in collaboration with Laureys, pressed on. They found that of 54 patients with disorders of consciousness, five were able to make tennis/house responses. Then, in 2009, Owen's postdoctoral student Martin Monti asked one of them, a 22-year-old who had been in a vegetative state for five years, to answer simple questions with his thoughts, using the output of the scans to communicate. "Do you have any siblings?" Monti asked, telling him to concentrate on tennis for yes or walking around his house for no. Using this crude binary system, the man answered five out of six questions correctly.

The Monti study could not determine how conscious this man is or whether his awareness is normal. Furthermore, there is no simple way to find out how many patients there are like him. Functional MRI is expensive and awkward, and transporting a brain-injured person for scanning is logistically daunting. Even Monti's star patient has not yet been able to return for further evaluation. And some brain-injured people who are indisputably conscious do not look that way in neuroimaging. Schiff's group has a subject, formerly vegetative, who can carry on a conversation and crack jokes but still cannot produce an intelligible signal in the fMRI.

Schiff's group now hopes to clarify this mess by finding a way to gauge the brain's status directly rather than through the filter of a scan. Schiff, 45, is intense; he speaks quickly in long, dense sentences jammed with subclauses and punctuated with wry laughter. Although he is now a professor of neurology and neuroscience at Weill Cornell and gets invitations to talk about his work all over the world, he is down-to-earth, as are the rest of his small team. The patients and their heartbreaking, humbling brains keep them that way.

Some subjects have unbelievable Rip Van Winkle stories. An Arkansas man named Terry Wallis spent 19 years in a minimally conscious state after a car accident and then abruptly woke up in 2003. "Mom," he said, then "Pepsi," and within days he was speaking fluently. Later, when Schiff and neuroimaging specialist Henning Voss brought Wallis to Weill Cornell, they caught his brain in the act of rewiring itself. Using diffusion tensor imaging (DTI), which can depict axonal fibers, they found a thick cable of what looked like new axons sprouting at the back of the patient's brain. This study was "incredibly important," Owen says; nobody would have believed that a brain could reconnect itself decades after it was injured—until it actually did.

There is also the case of George Melendez, a Texas man who, after nearly drowning, fell into a minimally conscious state and remained there for two years. He did not speak, but because he often groaned loudly at night, his mother got him a prescription for the sleeping aid Ambien. Hours after giving him the first pill, he seemed more alert than usual. "George?" she said, and he turned to her and asked, "What?" Now, nine years later, as long as he keeps taking the drug, he can feed himself and answer questions, even demonstrate baseball grips (he used to be a minor-league pitcher). Without it his hand shakes, he cannot eat, and he has trouble speaking. The sedative paradoxically keeps his brain awake: PET scans show that on Ambien, his brain uses twice as much fuel.

Schiff brings subjects one at a time to New York–Presbyterian Hospital to be scanned, measured, and probed for several days. PET/CT scans reveal how much energy their brains are using, and MRI shows which parts are damaged. While the team peppers a subject with questions, audiotapes, pictures, and other sensory prods, an fMRI machine tracks brain activity to look for evidence of awareness and the possibility of establishing communication. At other times, dozens of tiny electrodes are glued to the patient's scalp to pick up electrical signals through electroencephalography (EEG). Schiff repeats the clinical exam over and over, looking for fluctuations in awareness.

The scientists have now profiled more than 30 subjects, with some coming back as many as four times over the years. From these studies Schiff is developing a circuit diagram of the recovery of consciousness, a schematic that offers tentative explanations for some of the surprises he has seen. In this blueprint there is no single consciousness center of the brain. Instead, consciousness appears as a type of collective agreement among different brain regions, a dynamic state made possible by an active coalition of parts. "If somebody asked me 10 years ago, 'So, what's the circuit for consciousness?' I wouldn't have had a clue," Giacino says. "We can start to maybe answer that question now."

The circuit diagram focuses on the links among the central thalamus, the cortex, and regions (such as the globus pallidus and the striatum) that closely regulate the level of stimulation between cortex and thalamus. Schiff thinks that some of these regulatory mechanisms may actually prevent the damaged brain from restarting itself, and that pharmaceutical or electrical assistance can sometimes get it over that hurdle. That could explain Melendez and others like him who improve on Ambien: The drug might boost thalamic activity by blocking activity in the globus pallidus, which normally keeps the thalamus in check. Amantadine, a Parkinson's drug that simulates the natural brain chemical dopamine and activates the striatum, has also helped some people with disorders of consciousness, probably because it increases the striatum's inhibition of the globus pallidus, which in turn stops smothering the thalamus.

This schematic is a first step, a set of testable hypotheses about how an injured brain might climb back into awareness. It turns consciousness from a metaphysical question into a scientific one.

Remarkably, consciousness itself seems to heal the brain. Wallis,

CONTINUED ON PAGE 76

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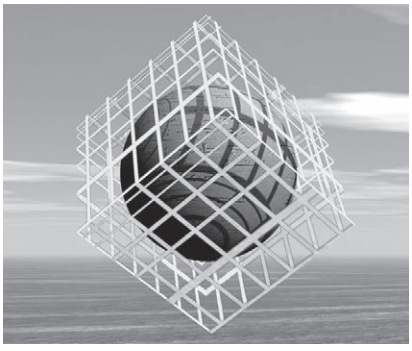

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a Distinguished Teaching Professor at The University of Texas at Austin. Professor Starbird has won several teaching awards, most recently the 2007 Mathematical Association of America Deborah and Franklin Tepper Haimo National Award for Distinguished College or University Teaching of Mathematics, which is limited to three recipients annually from the 27,000 members of the MAA.

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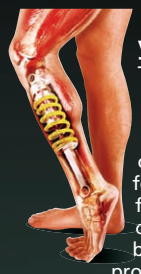

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CONTINUED FROM PAGE 71

Melendez, and the deep brain stimulation patient all continued to recover after their awakenings, perhaps because the fundamental mechanisms by which the brain remolds itself—through learning, memory, and normal sleep cycles—were put back online. Schiff thinks that once a brain reengages with the world, it will often restart processes of repair and renewal. "There is some aspect of recovery that requires the brain to be active in the process," he says.

IN HIS SEARCH FOR A BIOLOGICAL FINGERprint of the recovering brain, Schiff has identified a few brain-wave patterns common to Wallis, Melendez, and a handful of others who have made notable, though less spectacular, recoveries. In the transition to awareness, the squiggly EEG signals —electrical patterns generated by the collective activity of the neurons in the cortex —make a distinctive shift. Someone with a disorder of consciousness generates big, slow-rolling EEG waves that resemble those of a sleeping or anesthetized brain. With greater awareness, the slow swell gives way to faster, higher-frequency waves as more electrically active neurons kick in. These faster rhythms, between 25 and 40 hertz (cycles per second), typically signal concentration and normal alert thought. Many neuroscientists think they coordinate regions of the cortex to jointly analyze information. Schiff's team is now looking at the details of the shift, seeking signature patterns that could be detected with EEG. Cheap, portable, noninvasive, and relatively easy to use, EEG could be deployed in nursing homes and long-term care facilities to search for consciousness hidden from view. Depending on the pattern, signals might indicate which treatment to try for which patient and offer a means of evaluating the therapies. EEG could also be used to identify patients who need more careful inspection with neuroimaging.

In the future, more patients may benefit from deep brain stimulation, although the team is moving forward slowly with this project to be sure to pick the best subjects. As for those patients whose brains are trapped in inanimate bodies, implants that pick up electrical impulses can already translate neural signals to control a cursor, move a wheelchair, or say hello, although they are not now suitable for people with severe brain injuries. Owen predicts that within five years at least one patient who appears fully vegetative will, with the aid of some kind of brain–computer interface, be able to communicate routinely with the world.

Some patients' families have requested that fMRI be used now to ask them how they want to live or whether they might prefer to die. The answers provided by neuroimaging can be confounding. Recently, Schiff's grad student Jonathan Bardin tried to establish fMRI communication with a young woman who had been in what seemed to be a minimally conscious state for two years. A stroke had wiped out most of her brain stem and damaged her thalamus, but her cortex looked almost untouched on CT scans, and her brain metabolism was close to normal. Everything pointed to her being able to communicate if given the chance. Because she had been a competitive swimmer, Bardin asked her to imagine swimming to signal "yes" when shown the right answer to a multiple-choice question. The patient had responded correctly in a test of her ability to identify cards via eye movement, but when Schiff asked her to do the same thing via fMRI, she answered consistently, but consistently wrong. Did she misunderstand? Is she delirious? Nobody knows.

But sometimes the successes are unambiguous. One of the Schiff group's recent subjects was 23 years old when he sustained a severe head injury in a car crash. CT scans showed that his brain was ravaged, with a huge shadow of fluid where neural flesh should be. He spent three months in a vegetative state. A year after the accident, a physical therapist realized the patient could voluntarily move his head. The therapist trained him to use a letter board, in which a helper points to letters until the patient reacts, spelling out a message one letter at a time. His IQ turned out to be normal, and apparently his personality survived too; after several hours of being queried and quizzed by Schiff's team, he used the board to spell G-E-T O-U-T.

Schiff's team helped him acquire a head mouse, which allows him to use a computer by moving his head to control the cursor. He slowly continued to improve. Last winter, this man—who not long ago might have been abandoned as hopeless—sent Schiff's group an e-mail. Hi, it said; I'm doing well. It was a telegram from a future world.

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20 THINGS YOU DIDN'T KNOW ABOUT SPIDERS

BY REBECCA COFFEY

1. The venom of the Australian funnel-web spider can kill a person in less than an hour, and its fangs can bite right through a shoe. **2.** But for most people, fear of spiders is a far greater problem than the spiders themselves. Researchers at the University of São Paulo have developed an improbable way to undo arachnophobia by having patients stare at pictures of "spiderlike" objects—a tripod, a carousel, a person with dreadlocks. **3.** Quackery? Apparently not. In a 2007 study, the scientists reported a 92 percent success rate. **4.** And there is an upside to spider bites. Take the Brazilian wandering spider, *Phoneutria nigriventer*, whose venom causes painful penile erections that last for many hours (that's the bad news). **5.** The good news: The responsible toxin could yield new treatments for erectile dysfunction. **6.** The venom of the South American tarantula *Grammostola spatulata* might be used to treat atrial fibrillation. It contains a peptide that can calm an irregular heartbeat brought on by stress. **7.** Back in Australia, Glenn King at the University of Queensland is studying the Blue Mountains funnel-web spider (*Hadronyche versuta*) with an eye toward developing eco-friendly pesticides. Proteins in this spider's venom target the nervous system of insects but leave humans unharmed. **8.** First, though, there's the unpleasant matter of getting the venom. Workers at the Spider Pharm in Yarnell, Arizona, "milk" up to 1,000 spiders a day. **9.** The bugs are anesthetized with carbon dioxide, then zapped with electricity, which makes them release venom into minuscule glass capillaries connected to their fangs. **10.** Web master: Todd Blackledge at the University of Akron finds that spider silk could be used as synthetic muscle. Adjusting humidity up and down causes the silk to expand and contract with 50 times the punch of the equivalent mass of human muscle. **11.** Blackledge envisions spider silk someday being used to operate miniature robotic devices and drug delivery systems. **12.** Unlike many sticky things, the glue of orbed web spiders gets stronger in the presence of water, polymer scientists working with Blackledge have discovered, suggesting that it might prove a useful adhesive for surgery or for underwater engineering. **13.** Spider-goat, Spider-goat, does whatever a spider can: By manipulating genes, molecular biologists at the University of Wyoming have gotten goats to produce milk containing the protein that makes up spider silk. **14.** Next, scientists aim to introduce the silk gene into alfalfa, which is far more efficient to mass produce and, frankly, less creepy. **15.** Safe sex: The male nursery web spider (*Pisaura mirabilis*) will bring a silk-wrapped insect to a female prior to mating so she will eat the gift—instead of him. **16.** Safer sex: The funnel-web spider *Agelenopsis aperta* has a different approach, putting the female into a cataleptic state before mating so she won't cannibalize him. **17.** Scientists at Radford University in Virginia say the *A. aperta* male can disable the female from 4.5 centimeters (about 2 inches), suggesting he may be deploying a gas to knock out the femme fatale. **18.** Cheap date: Certain cobweb spiders dine on bugs poached from others' webs. **19.** Others dispense with the killing entirely. The jumping spider *Bagheera kiplingi*—named in the 1800s after the panther in Rudyard Kipling's *Jungle Book*—is mostly a vegetarian. **20.** Don't want one of these things jumping in your salad? Steven Kutcher, spider wrangler on the film *Arachnophobia,* says a dusting of talcum powder or a spritz of Lemon Pledge makes a tabletop or other flat surface too slippery for the critters to get any traction.

MICHAEL & PATRICIA FOGDEN/MINDEN PICTURES

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